HYDRATED LIME

HISTORY
MANUFACTURE
STANDARD SPECIFICATIONS
STRENGTHENING AND WATERTIGHTENING
CEMENT MORTARS AND CONCRETE
PRACTICAL APPLICATION
USE IN MORTARS

BY E. W. LAZELL, PH. D.

Hydrated Lime

History, Manufacture and Uses in
Plaster - Mortar - Concrete

1915

A Manual For
The Architect, Engineer,
Contractor and Builder.

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Pyramid of Cheops.

CHAPTERS

LIST OF ILLUSTRATIONS

INTRODUCTION

IN presenting this book to the public, the purpose has been to direct the attention especially of architects and builders to the comparatively new form of lime "Hydrated Lime," which possesses many advantages over the older Lump Lime.

The art of using lime is one of the very oldest connected with the building trade and was probably brought to its greatest perfection by the Greeks and Romans. Since these ancient times until very recently little or no improvement has been introduced in the preparation of plaster or stucco made from lime. Probably the reason for this is the time and care required to slake the lump lime used to prepare the mortar. With the use of hydrated lime the time required to slake and age the quick lime is done away with.

It has been my aim to collect together in convenient form the available data on this subject. Use has been made of previous publications and much information has been obtained from the technical press. Especial mention must be made of the works of Vitruvius, Vicat, Miller and Hodgson and the various publications of the different Bureaus of the United States Government. It is hoped that the book may prove useful in calling attention to the characteristics of hydrated lime and describing its various uses.

1915 E. W. LAZELL, Ph. D.

HISTORICAL

CHAPTER I

THE use of lime as a binding material or mortar for holding together stone and brick originated in the remote past. It is probable some savages, having used stones composed of limerock to confine their fire, noticed that the stones were changed by the action of the heat. A passing shower slaked the lime to a paste, thus the discovery was made that the paste was smooth working and furnished a better material than clay to fill up the holes and crevices in their crude dwellings. From the discovery of the fact that burned limerock gave a material which slaked with water to a paste, it was but a step to the addition of sand in order to produce a mortar.

The art of using mortar in some form or other is as old as the art of building or as civilization itself. Evidences of the use of mortar are found not only in the older countries of Europe, Asia and Africa, but also in the ruins of Mexico and Peru. The remains of the work of these ancient Artisans are evidence to us of the enduring qualities of lime mortar as well as the skill and knowledge possessed by the user. Miller in his work on mortar states "Plastering is one of the earliest instances of man's power of inductive reasoning, for when men built they plastered; at first, like the birds and beavers, with mud; but they soon found out a more lasting and more comfortable method, and the earliest efforts of civilization were directed to plastering. The inquiry into it takes us back to the dawn of social life until its origin becomes mythic and prehistoric. In that dim, obscure period we cannot penetrate far enough to see clearly, but the most distant glimpses we can obtain into it shows us that man had very early attained almost to perfection in compounding material for plastering. In fact, so far as we yet know, some of the earliest plastering which has remained to us excels, in its scientific composition, that which we use at the present day, telling of ages of experimental attempts. The pyramids of Egypt contained plaster work executed at least 4000 years ago, and this, where wilful violence has not disturbed it, still exists in perfection, outvying in durability the very rock it covers, where this is not protected by its shield of plaster."

The earliest known examples of the employment of mortar in masonry are presented by the pyramids of Egypt. Vicat in his celebrated treatise on Mortars and Concrete, states: "The Egyptian monuments present without doubt the most ancient and remarkable

examples which we can quote of the use of lime in building. The mortar which binds the blocks of the pyramids, and more particularly those of Cheops, is exactly similar to our mortars in Europe. That which we find between the joints of the decayed buildings at Ombos, at Edfou, in the Island of Phila, and in other places, gives evidences by its color, of a reddish very fine sand mixed with lime in the ordinary proportion. The use of cements (limes) was therefore already known two thousand years before our time; perhaps it would be easy to carry that epoch still farther back, were we to consult the ancient monuments of India, and the Sanscrit books, if they speak of the ancient relations of Egypt with that country; but this would be to attach too much importance to an inquiry, more curious than useful."

At a very early period the Greeks used plaster consisting of a true lime stucco of most exquisite composition, thin, fine and white. The houses of the simple citizen were ornamented with stucco which for whiteness, hardness and polish compared well with the Parian marble. Thus at the time of Pericles and Plato, the art of plastering had made great progress. From the Greeks the Etruscans, of middle Italy, gained their knowledge and the Romans in turn learned the art of plastering from them. Greece became a Roman province in 145 B. C., and the loot of it gave a great impetus to Roman art. Our knowledge of the Roman methods of building and their use of material is largely derived from the writings of Vitruvius. Vitruvius was a military engineer under Julius Ceasar in his African campaign and was an architect under Augustus. On all matters relative to Greek and Roman architecture, Vitruvius should be consulted, since according to his own confession his work contained all the knowledge that the Greeks possessed of the art of building. Pliny the elder, in his natural history, and Palladius, have added nothing to what Vitruvius had said before them. The writings of Vitruvius will be referred to later in other chapters, since his monumental work on architecture remained a standard reference book until well into the 18th Century.

The Arabians and Moors both became experts in plastering as is evident by the splendid plaster work still to be seen on the Alhambra.

As early as the beginning of the 16th Century, the art of plastering had made considerable progress in England and "The Plasterers Company" was incorporated in 1501.

This brief review of the art of plastering as practiced by the Ancients, will give an idea of the possibilities of the use of lime as well as proving its enduring qualities. It is indeed sad to state that the present status of the art does not nearly reach the perfection attained by the Greeks and Romans, and it is with a wish to interest the public in the various uses of lime mortar that this treatise was undertaken.

CHEMISTRY OF LIME

CHAPTER II

ANY change which alters the composition and structure of matter is a chemical change. A familiar illustration of this is the burning of coal in which case both the composition and structure are changed. It therefore follows since the structure and composition of lime are changed by burning that a chemical reaction has taken place. If the changes brought about by burning and slaking lime are to be understood some knowledge of chemistry is necessary.

From a chemical standpoint, the changes which take place in the manufacture of lime from limestone and the subsequent changes in slaking and hardening are comparatively simple and do not involve an extended knowledge of chemistry. In order to render the subject clear, the various chemical terms involved will be explained and defined.

All matter is made up of one or more elementary substances, or chemically speaking, all matter is made up of one or more elements. *An element is a primary form of matter which cannot be reduced to a simpler form by any means known to science.* There are some 80 of these elementary forms of matter known, and of these only about a dozen are involved in the chemistry of lime. These elementary substances combine with each other forming compounds in a certain known definite manner. *Thus a compound is the product resulting from the union of two or more dissimilar elements.*

Modern science recognizes three divisions of matter, *Mass*, *Molecule* and *Atom*. Mass alone is appreciable to the senses. The other divisions being far too minute to be reached by any power of observation. *Molecule is the term used to designate the smallest particle of matter that can exist and still preserve the properties of the substance.* It is formed by a union of atoms which may be like or unlike, few or many; it is constant and regular in the disposition of its parts and bound together by strong forces. The use of the term "atom" is from theoretical rather than experimental considerations. Experiment has shown that a definite quantity of each element always enters into combination, and theory assumes that the smallest quantity entering into any combination is an "atom." *An atom can be defined as the smallest part of an element that can enter into combination with another element.*

Although the atom in all cases is too small to be weighed individually, the relative weight of each kind of atom has been carefully obtained as the result of experiment. The weights of the various atoms have been determined relatively by comparing them with hydrogen (the lightest known element) which is taken as unity or one. These relative weights are called the "Atomic Weights."

TABLE No. 1

Atomic weights of the common elements

Name	Chemical Symbol	Atomic Weights
Hydrogen	H	1
Oxygen	O	16
Carbon	C	12
Calcium	Ca	40
Magnesium	Mg	24
Aluminum	Al	27
Iron (ferrum)	Fe	56
Silicon	Si	28
Sulphur	S	32

NOTE—The atomic weight is given to the nearest whole number as this is sufficiently accurate.

The atomic weight of an element means that the weight of its atom is so many times heavier than the weight of an atom of hydrogen. For example, the weight of an atom of oxygen is 16 times greater than that of an atom of hydrogen.

For convenience abbreviations are used for all elements. These abbreviations are known as *Chemical Symbols.* Chemical Symbols serve not only as an abbreviation for the name of the element, but the chemist employs them to indicate the composition of the compound and the number of atoms of the element in the compound. Thus the symbol for calcium carbonate is written $CaCO_3$. In which "Ca" stands for calcium, "C" for carbon and "O" for oxygen. The symbol further indicates that there is present in each molecule of calcium carbonate one atom of "Ca," one atom of "C" and three atoms of "O." If the atomic weight of the elements are inserted in the place of the symbol, we have $Ca=40$, $C=12$, $O=16$, $O_3=48$, total $40+12+48=100$, the molecular weight of calcium carbonate. *The molecular weight of a compound therefore is the sum of the weights of the atoms making up the compound.*

Knowing the molecular weights of a substance and the elements of which it is composed, it is possible to calculate its percentage

composition. As an illustration, take calcium carbonate, the percentage of each element present is:

Ca 40/100 = 40%
C 12/100 = 12%
O 48/100 = 48%

Calcium carbonate can also be considered as composed of calcium oxide (CaO) and carbon dioxide (CO_2).

Calcium oxide	(Ca+O)	40+16 = 56
Carbon dioxide (carbonic acid gas)	($C+O_2$)	12+32 = 44
		100

Therefore, there is present in calcium carbonate:

56/100 = 56% CaO (lime)
44/100 = 44% CO_2 (carbon dioxide)

The compounds of the above elements most useful to the student of lime are the oxides, hydroxides, hydrates and carbonates. These various compounds of the elements given in Table No. 1 are illustrated in Table No. 2.

TABLE No. 2

Elementary Substance or Element			Union of Two or More Elementary Substances or Compounds								
			With Oxygen Oxides			With Water Hydroxides Hydrates			With Carbon Dioxide Carbonates		
Name	Symbol	Atomic Weight	Name	Symbol	Molecular Weight	Name	Symbol	Molecular Weight	Name	Symbol	Molecular Weight
Hydrogen	H	1	Water	H_2O	18						
Oxygen	O	16									
Carbon	C	12	Carbon Dioxide	CO_2	44						
Calcium	Ca	40	Calcium Oxide Lime	CaO	56	Calcium Hydroxide	$Ca(OH)_2$	74	Calcium Carbonate	$CaCO_3$	100
Magnesium	Mg	24	Magn'm Oxide Magnesia	MgO	40	Magnesium Hydroxide	$Mg(OH)_2$	58	Magnesium Carbonate	$MgCO_3$	84
Aluminum	Al	27	Alumn'm Oxide Alumina	Al_2O_3	102	Aluminum Hydroxide	$Al_2(OH)_6$	156			
Iron (Ferrum)	Fe	56	Ferric Oxide	Fe_2O_3	160	Ferric Hydroxide	$Fe_2(OH)_6$	214			
Iron	Fe	56	Ferrous Oxide	FeO	72	Ferrous Hydroxide	$Fe(OH)_2$	90			
Silicon	Si	28	Silicon Oxide Silica	SiO_2	60						
Sulphur	S	32	Sulphur Dioxide	SO_2	64						

BURNING—The chemical change which takes place in burning lime consists in destroying the bond between the calcium oxide and carbon dioxide. This change is illustrated by using the chemical symbols in the form of an equation and for a perfectly pure calcium carbonate the chemical change can be illustrated as follows:

Calcium carbonate (limestone)	+ heat =	calcium oxide (lime)	+ carbon dioxide (gas)
$CaCO_3$	+ heat =	CaO	$+ CO_2$
100	+ heat =	56	+ 44

This equation shows that the calcium carbonate has been broken up into two dissimilar substances by the action of heat, one of which is a solid (lime) and the other a gas (carbon dioxide). Further, it indicates that 100 parts by weight of calcium carbonate yield 56 parts by weight of lime, and that 44 parts by weight of carbon dioxide are driven off by heat.

In the change produced by burning, the gas (carbon dioxide) is carried out of the kiln together with the products of combustion of the fuel. Nothing but the carbon dioxide is removed, except any moisture or organic matter which may have been present in the stone. The solids, lime, magnesia and all other substances, remain in the burned lime.

If the limestone contained 5% of impurities, such as silica or clay, these would have remained in the burned product. In this case in 100 parts of the impure stone there would be 95 parts of calcium carbonate. These 95 parts of calcium carbonate would yield $95/100 \times 56 = 53.2$ parts of calcium oxide, the total matter remaining after burning would be $53.2 + 5$ or 58.2 parts of impure lime, since the 5 parts of impurities cannot be removed by burning.

The percentage composition of the burned lime would be:

$$\frac{53.2}{58.2} = 91.4\% \text{ calcium oxide}$$

$$\frac{5}{58.2} = 8.6\% \text{ impurities}$$

The presence therefore of 5% of silica or clay in the original limestone has reduced the amount of lime (calcium oxide) in the burned product from 100% to 91.4% or nearly 9%.

In a similar manner the burning of a dolomitic limestone may be illustrated as follows:

Dolomite			+ heat =	Dolomitic lime			
Calcium and magnesium carbonate			+ heat =	calcium and magnesium oxide			+ carbon dioxide
$CaCO_3$,	$MgCO_3$		+ heat =	CaO,	MgO		+ $2CO_2$
100	84	(184)	+ heat =	56	40	(96)	+ 88

The percentage composition of the dolomitic lime would be as follows:

$$\frac{56}{96} = 58.34\% \text{ Calcium oxide (CaO)}$$

$$\frac{40}{96} = 41.66\% \text{ Magnesium oxide (MgO)}$$

One hundred and eighty-four pounds (184 lbs.) of dolomitic limestone yield 96 lbs. of dolomitic lime or 52.17% ($96 \div 184 = 52.17\%$): that is 100 lbs. of dolomite yields only 52.17 lbs. of dolomitic lime, consisting of the oxides of calcium and magnesium.

From the preceding equations it will be seen that the amount of impurities present in the stone increased the yield of the burned product, although at the same time it decreased the amount of oxides of calcium and magnesium present in the burned material (5 lbs. of impurities present in the stone decreases the amount of the oxides of calcium and magnesium contained in the burned product to about 91%). Further it will be noted that 100 lbs. of dolomitic limestone gave only 52.17 lbs. of burned material, while 100 lbs. of high calcium limestone gave 56 lbs. of burned material, thus the presence of magnesia decreases the yield from 100 lbs. of stone.

SLAKING OR HYDRATING LIME

As is well known, when quick-lime is treated with water, heat is generated and a product is formed which has an entirely different character than the original quicklime. This indicates that a chemical reaction has taken place which can be expressed for the two groups of limes as given below:

High calcium quicklime	+ water	= high calcium hydrate
CaO	$+ H_2O$	$= Ca(OH)_2$
56	+ 18	= 74

In this reaction 56 parts by weight of high calcium quicklime have combined with 18 parts by weight of water producing 74 parts by weight of dry hydrate. This dry hydrate contains the original amount (56 parts) of quicklime, but this material is not present as quicklime since

it has chemically combined with the water. In case more than the exact amount of water necessary to form the chemical hydrate is present, this water is simply mechanically mixed with the hydrate forming a lime paste. Calcium oxide is the only compound present in the lime which actively combines with water, in the ordinary methods of slaking.

For dolomitic quicklime the reaction of slaking is expressed by the following equation:

Dolomitic quicklime + water = Dolomitic hydrate

$$CaO\ MgO + H_2O = Ca(OH)_2\ MgO$$

$$96 + 18 = 114$$

By comparing this equation with the one for high calcium quicklime it will be noticed that less water has been combined in the slaking. The reason for this is that the magnesium oxide contained in dolomite is rendered inert at the temperature of burning and does not combine chemically with the water, but remains present in the hydrate as magnesium oxide. Thus dolomitic hydrate consists of a mixture of calcium hydrate and magnesium oxide. It is for this reason that it requires a greater weight of dolomitic quicklime to produce the same weight of hydrate. The amount of caustic oxides present in the dolomitic hydrate is greater than in the high calcium hydrate. The above equation was calculated for a pure dolomite containing 58.5% lime and 41.5% magnesia.

Hardening—The hardening of lime mortar is due to the lime and magnesia present in the mortar combining with the carbon dioxide of the atmosphere. The chemical change that takes place can be illustrated by the following equation:

Calcium hydrate + Carbon dioxide = Calcium carbonate + water

$$Ca(OH)_2 + CO_2 = CaCO_3 + H_2O$$

$$74 + 44 = 100 + 18$$

Magnesium oxide + Carbon dioxide = Magnesium carbonate

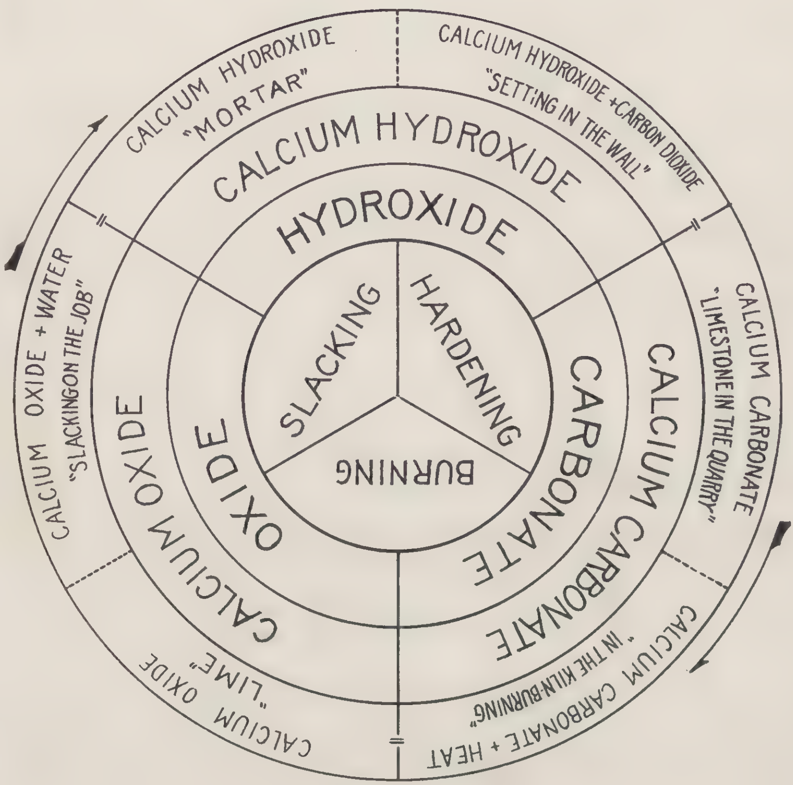
$$MgO + CO_2 = Mg\ CO_3$$

$$40 + 44 = 84$$

From the foregoing explanation, it will be seen that lime passes through three distinct chemical phases in its change from the stone to the hardened mortar. These three phases form a cycle, and in the end lime has returned to its original form. These three changes have been illustrated and are given below:

1st—Burning	$CaCO_3 + \text{heat} = CaO + CO_2$
2nd—Slaking	$CaO + H_2O = Ca(OH)_2$
3rd—Recarbonating (hardening)	$Ca(OH)_2 + CO_2 = CaCO_3 + H_2O$

These changes have been graphically illustrated by the author as the "Lime Cycle." Page No. 17.



Lime Cycle

Showing the Sequence of the Changes Produced by Burning, Slaking and Hardening, and that these Changes Form a Complete Cycle; the Lime Returning to its Original Carbonate Form.

A familiarity with the chemical terms and the changes which take place in the manufacture and use of lime has a further advantage both to the manufacturer and user in that it renders easy the interpretation of the results of a chemical analysis of limestone and lime. This can best be explained by starting with the analysis of a natural sample of limestone and dolomite and following the two cycle change produced by burning and slaking.

Chemical Terms	Symbol	High Calcium Limestone Per Cent.	Dolomitic Limestone Per Cent.
Silica	SiO_2	1.00	.93
Alumina / Ferric oxide	Al_2O_3 / Fe_2O_3	.90	.39
Lime	CaO	54.24	32.73
Magnesia	MgO	.80	19.37
Carbon dioxide / Water (Loss on Ignition)	CO_2 / H_2O	43.06	46.58

All the above ingredients may be classed under three heads; impurities: silica, alumina and iron oxide; material removed by burning: carbon dioxide and water; and the lime ingredient: lime and magnesia, the only two materials which confer valuable properties on the burned product.

It is possible from the above analysis to calculate the composition of the lime which would be produced by burning either of the above stones. The amount of material indicated by loss on ignition is that portion which is driven off, all the other ingredients remaining in the burned product. It follows therefore, that from 100 parts of the above high calcium stone there would remain after burning only 56.94 parts of high calcium lime (100 − 43.06 [loss on ignition] = 56.94). The quantities of the various ingredients other than those included in loss on ignition are present in the lime; therefore, the percentage composition of the burned lime is calculated as follows:

$$SiO_2 \text{ in lime } \frac{1.00}{100-43.06}=\frac{1.00}{56.94}= 1.76\%$$

$$Al_2O_3+Fe_2O_3 \qquad \frac{.90}{56.94}= 1.58\%$$

$$CaO \qquad \frac{54.24}{56.94}=95.26\%$$

$$MgO \qquad \frac{.80}{56.94}= 1.40\%$$

The composition of the lime produced from the dolomitic limestone is derived in a similar manner:

$$SiO_2 \qquad \frac{.93}{100-46.58}=\frac{.93}{53.42}= 1.74\%$$

$$Al_2O_3+Fe_2O_3 \qquad \frac{.39}{53.42}= .73\%$$

$$CaO \qquad \frac{32.73}{53.42}=61.27\%$$

$$MgO \qquad \frac{19.37}{53.42}=36.26\%$$

These illustrations show that in order to derive the composition of any lime produced from a stone of known analysis it is only necessary to divide the percentage amount of the ingredient by the difference obtained by subtracting the percentage given for the loss on ignition from 100.

The calculation of the composition of the hydrates derived from the above limes by slaking is not quite so simple, still nothing is involved more complicated than the rule of three. As has been stated before, lime is the only compound present which combines with water, and this combination takes place according to the equation

$$CaO+H_2O=Ca\,(OH)_2$$
$$56 \quad +18 \quad =74$$

or each 56 parts by weight of lime give 74 parts of hydrate; then the 95.26 parts of lime would give:

$$56:74 \text{ as } 95.26:X \qquad X=125.88$$

100 parts of the high calcium lime would yield on hydrating as follows:

SiO_2	No change	1.75 parts
$Al_2O_3+Fe_2O_3$	No change	1.58
CaO	Change to hydrate	125.88
MgO	No change	1.40
	Total	130.61

The percentage composition of this hydrate would be as follows:

$$SiO_2 \qquad \frac{1.75}{130.61}= 1.34\%$$

$$Al_2O_3+Fe_2O_3 \qquad \frac{1.58}{130.61}= 1.21\%$$

$$Ca(OH)_2 \qquad \frac{125.88}{130.61}=96.38\%$$

$$MgO \qquad \frac{1.40}{130.61}= 1.07\%$$

In the same manner, the hydrate produced from the dolomitic lime can be calculated. In this lime there is 61.27% of lime and this amount would yield on hydration as follows:

$$56:74 = 61.27:X \quad X = 80.96$$

SiO_2	No change	1.74 parts
$Al_2O_3 + Fe_2O_3$	No change	.73
$Ca(OH)_2$	Changed to hydrate	80.96
MgO	No change	36.26
	Total	119.69

The percentage composition of this hydrate would be as follows:

$$SiO_2 \quad \frac{1.74}{119.69} = 1.45\%$$

$$Al_2O_3 + Fe_2O_3 \quad \frac{.73}{119.69} = .61\%$$

$$Ca(OH)_2 \quad \frac{80.96}{119.69} = 67.65\%$$

$$MgO \quad \frac{36.26}{119.69} = 30.29\%$$

In the foregoing the attempt has been made to explain clearly and simply the chemical changes which take place in the manufacture and use of lime—some knowledge of this subject is necessary for the manufacturer if the material is to be prepared in a proper manner. The user of lime also should understand the action of burned lime if the material is to be handled to the best advantage.

CLASSIFICATION OF LIME

CHAPTER III

ORIGIN Limestone is the raw material from which lime is manufactured. In general, limestones have been formed by accumulation of remains of sea organisms, such as the foraminifera, corals and mollusks at the bottom of the sea. These limestones sometime show the fossil remains from which they were formed while in other instances all trace of their organic origin has been destroyed.

DEFINITION OF LIMESTONE The term "limestone" as used in the lime industry may be defined as *a general term referring to that class of rocks containing 80% or over of the carbonates of calcium and magnesium, which, when calcined, give products which slake upon the addition of water.* Limestones are generally differentiated geologically, based upon their different origin, texture and composition. Depending upon their physical appearance, the most important varieties are as follows:

CLASSES OF LIMESTONE *Marble*—Limestone having a coarse or fine crystalline structure which has been produced by heat and pressure.

Chalk—A soft friable limestone composed of finely divided shells consisting principally of those of the foraminifera.

Oolitic Limestone—(Oolite)—A limestone made up of small rounded grains so named because of its supposed resemblance to fish-roe.

Marl—A soft friable material made up of grains of carbonate of lime generally found in lake basins.

COMPOSITION OF LIMESTONE Depending upon their composition, limestones are generally distinguished as follows:

Argillaceous or clayey limestone, containing considerable clay.

Arenaceous or silicious limestone, containing considerable silica or sand.

Conglomerate Limestone, containing large pebbles of lime-rock.

Dolomite, a double carbonate of calcium and magnesium containing when pure 54.35% of calcium carbonate and 45.65% of magnesium carbonate.

Magnesian Limestone, containing between 10 and 30% of magnesium carbonate.

High Calcium Limestone, a limestone containing not more than 10% of magnesium carbonate.

NOTE—The preceding defiinitions are taken largely from the paper presented by Irving Warner and the author before the National Lime Manufacturers' Association in 1910.

Definition of Lime Lime may be defined *as the product resulting from the calcination of a limestone consisting essentially of the carbonates of calcium and magnesium, which slakes upon the addition of water.*

Since all limes are made from limestone, it follows that a classification of lime might be introduced which would indicate the origin of the lime or the kind of stone from which it was made. Following this system, the term "Marble lime" would indicate that the lime was produced from marble; "Argillaceous lime" one produced from a argillaceous limestone and the "Silicious lime" one produced from a silicious limestone, etc. Such a classification, however, would have little practical value for the building trades. A more rational classification is therefore based upon the chemical composition of the stone and the form in which the lime is brought into the market.

Types of Lime Classification of lime based upon the chemical composition:

(a) *High Calcium Lime*—Containing at least 90% of calcium oxide.

(b) *Calcium Lime*—Containing from 85% to 90% of calcium oxide.

(c) *Magnesian Lime*—Containing from 85% to 90% of calcium and magnesium oxides, 10% to 25% being magnesium oxide.

(d) *High Magnesium Lime*—Containing not less than 85% of calcium and magnesium oxide, not less than 25% being magnesium oxide.

(e) *Hydraulic Lime*—Which contains so large a percentage of lime silicate, aluminate or ferrate as to give the material the property of hardening under water, but which at the same time contains so much free lime that the burned mass will slake upon the addition of water.

Building Trades Classification of Lime Classification of lime and lime products based upon the form in which they are supplied the trade:

(a) *Run of Kiln Lime*—The product as it comes from the kiln, without any sorting or further preparation.

(b) *Selected Lump Lime*—A well burned lime which has been freed from core, ashes and cinder by sorting.

(c) *Ground or Pulverized Lime*—Lime which has been reduced in size to pass a ¼ inch screen.

(d) *Hydrated Lime*—A dry flocculent powder resulting from the treatment of quicklime with sufficient water to satisfy chemically all the calcium oxide present.

The various kinds of lime mentioned under the chemical classification may be brought into the market in any of the above four forms. For example, hydrated lime may be prepared from a high calcium, calcium, magnesian or high magnesian lime.

Classification of Limes as Fat, Lean or Hydraulic The terms fat and lean are often applied to lime and refer only to the working qualities of the paste and not to the chemical composition. A fat or rich lime is a term employed by the users of lime, to express smooth working qualities and great sand carrying capacity. A lean or poor lime is the opposite of a fat lime.

Lieut. W. H. Wright in his book on Mortars published in 1845 classified limes as follows: "Lime which is used for building purposes is rarely pure lime, but besides water and carbonic acid imbibed from the atmosphere contains usually some foreign substances. These substances modify the properties of pure lime, and, when combined with it in certain proportions, entirely change its nature. It will therefore be convenient to arrange the limes employed in construction into four different classes, 1st, the fat limes; 2nd, the poor or meager limes; 3rd, the hydraulic limes and 4th, the hydraulic cements.

"The fat limes are more than doubled in volume during the process of slaking, which is always attended with much heat. If converted into paste and immersed in water, they will remain of a soft consistency forever * * * . Builders call them fat limes, because the paste, which they form with water, is soft and unctuous to the touch.

"The poor or meager limes include all those which, in slaking, do not undergo an increase of volume equal to twice their original bulk, but exhibit, when immersed, the same qualities as the rich limes, * * *.

"The hydraulic limes possess the property of setting under water, in periods of time varying from one to forty days after immersion, and continue to harden more or less rapidly, according to the hydraulic energy which they respectively possess. They all slake, but with difficulty; the stronger kinds exhibiting few or none of the appearances usually seen in fat lime during the slaking process, little or no vapor being formed, and scarcely any heat disengaged; and they undergo an increase of volume, in the inverse ratio of their hydraulic energy.

"The hydraulic cements differ from the limes, in not slaking at all after calcination, unless they are previously pulverized; and they then form a paste with water, without any perceptible disengagement of heat, or augmentation of volume. They contain a large amount of the hydraulic base or principle, and set under water in a much shorter time than the limes require to set in air."

The classification of lime based upon the chemical composition and the form in which the material is brought into the market is the most concise and clear, and it is recommended that this classification be used.

MANUFACTURE OF LIME

CHAPTER IV

LIME is produced by expelling the carbon dioxide contained in limestone by means of heat. To accomplish this, it is necessary to heat the stone to the temperature of decomposition and further to supply sufficient heat to liberate the gas from the stone, or, in scientific terms, to break the chemical bond between the calcium and magnesium oxides and the carbon dioxide. It is not sufficient simply to heat the stone to the point of decomposition, but it is necessary to hold the stone at this temperature and to supply more heat in order to accomplish the disruption of the bond. This disruption does not take place at once, but requires time; hence, the stone must be retained in the burning zone long enough for the heat to accomplish its purpose.

Since it is necessary only to supply sufficient heat to the limestone to obtain lime, the earliest methods of burning were very simple and required but little skill. Perhaps the earliest method of burning was a heap of stones on the ground with logs used as fuel.

Type of Kilns These can be divided into two general classes as follows:
1st—Intermittent Kilns.
2nd—Continuous Kilns.

Pot Kiln 1st—Intermittent kilns, usually called "pot kilns," are those in which each burning of a charge constitutes a separate operation. The kiln is charged, burned, cooled, and then drawn. After completing the cycle, the kiln is recharged for another burning. Such a kiln often consists of a crude shaft excavated in the side of a hill; the interior of the shaft being lined with larger stones of the same material as those to be burned. At the bottom of the shaft, there is a horizontal passage to the outside. At the place where the horizontal passage meets the vertical shaft, an arch of limestone is made, and on top of this, more limestone is placed until the shaft is completely filled. A fire is then built under the arch, and the burning is continued until the stone is thoroughly calcined. Page No. 25.

Pot Kiln

An Early Form of Lime Kiln

Field Kiln At a somewhat later date, kilns were built in the open having vertical walls of masonry of a circular or square section but in other ways resembled the shaft in the side of the hill. These early types of shaft kilns are still to be found scattered throughout the country. A description of such a kiln given by Chas. T. Jackson, in the Third Annual Report on the Geology of Maine, published in 1839, states that this type of kiln was usually "built of refractory rock, lined with clay and laid outside with mortar 15 ft. wide—15 ft. high—5 ft. back Arches middle, 5 ft. high—side arches, 3½ ft. high. This kiln is the form commonly used at Thomaston, and the lime is burned by means of wood fuel, 30 cords of wood being required to burn the charge of rock. The operations are divided into four turns, and for three or four days and nights the fire is kept unremittently in action." Page No. 26.

Field Kiln
Described by Jackson in 1839

Such a kiln would produce about 300 casks, or 45 tons of lime at a burning. Jackson further states that similar kilns were constructed of a circular form.

This type of kiln commonly called a Pot Kiln can never be economical since there is an enormous loss of heat at each burning owing to the quantity of fuel required to raise the contents of the kiln and the surrounding thick stone walls to the necessary temperature each time the kiln is charged. Further, the stone nearest the arch is liable to become overburned before the top portion of the charge is calcined.

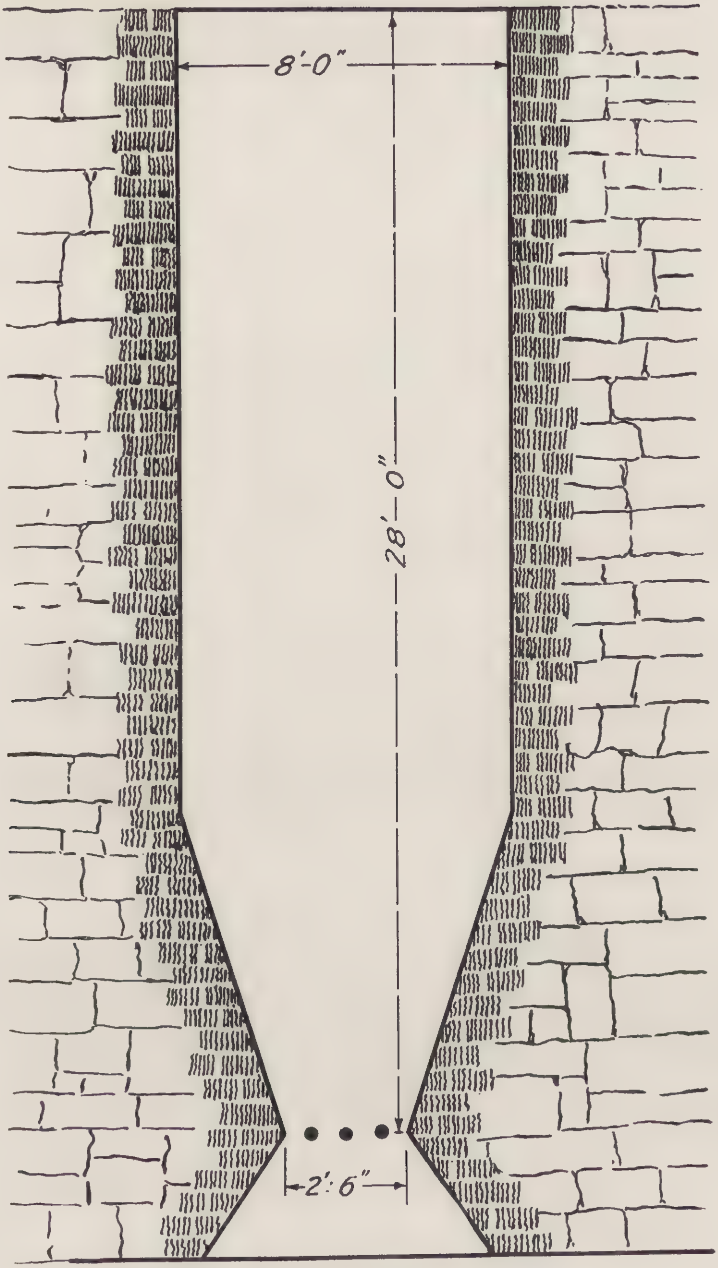
Continuous Kilns

This class can be subdivided as follows:

(a) Vertical kilns, mixed feed.
(b) Vertical kilns, separate feed.
(c) Ring, or chamber, kilns.
(d) Rotary kilns.

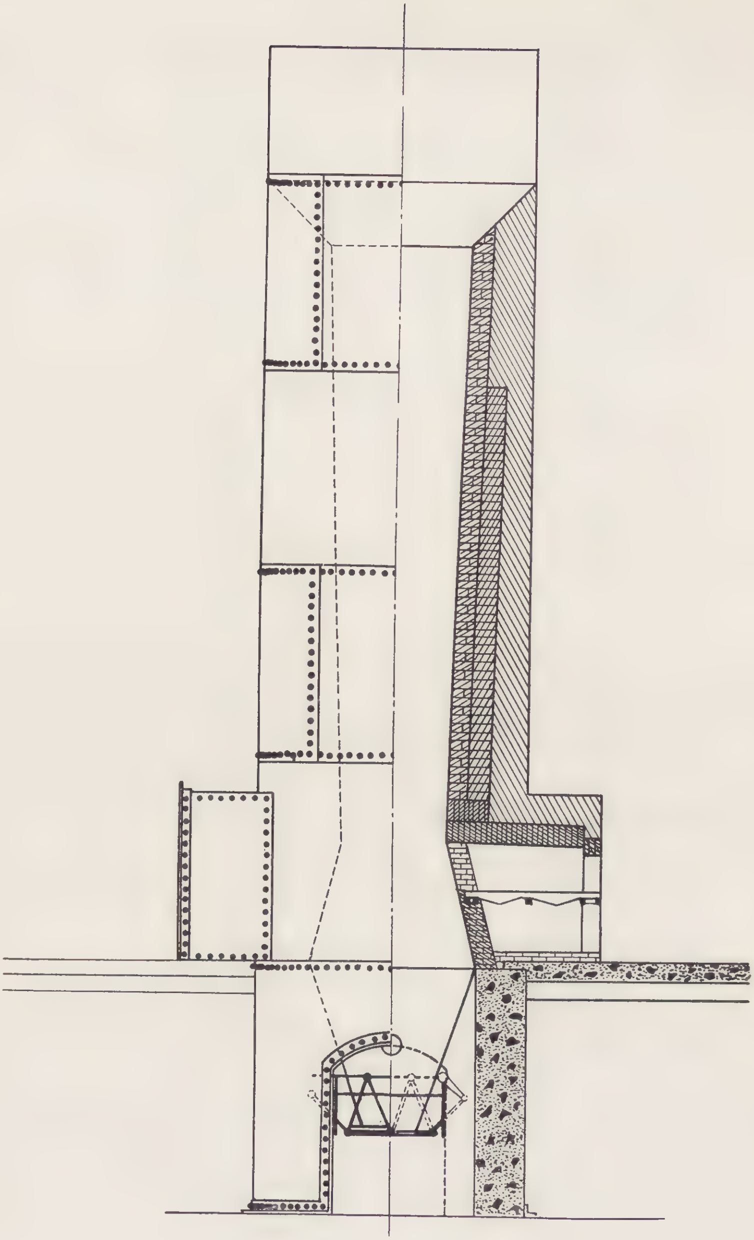
Draw Kiln

(a) *Vertical Kiln, Mixed Feed*—This type of kiln, generally called a draw kiln, is similar to the pot kiln; the limestone and fuel are charged at the top in alternate layers, and the burning proceeds from a point near the top, the lime being withdrawn at the bottom. The advantage of this type of kiln is that it is cheap to construct, and is economical in fuel. Its disadvantage is the discoloration and contamination of the burned lime by the ashes from the fuel; also the ashes combine with the lime, producing lumps which prevent thorough and satisfactory slaking. An early kiln of this type is illustrated herewith; this kiln was one in use at Thomaston, Maine, in 1838, anthracite coal screenings being used as fuel. Page No. 27.



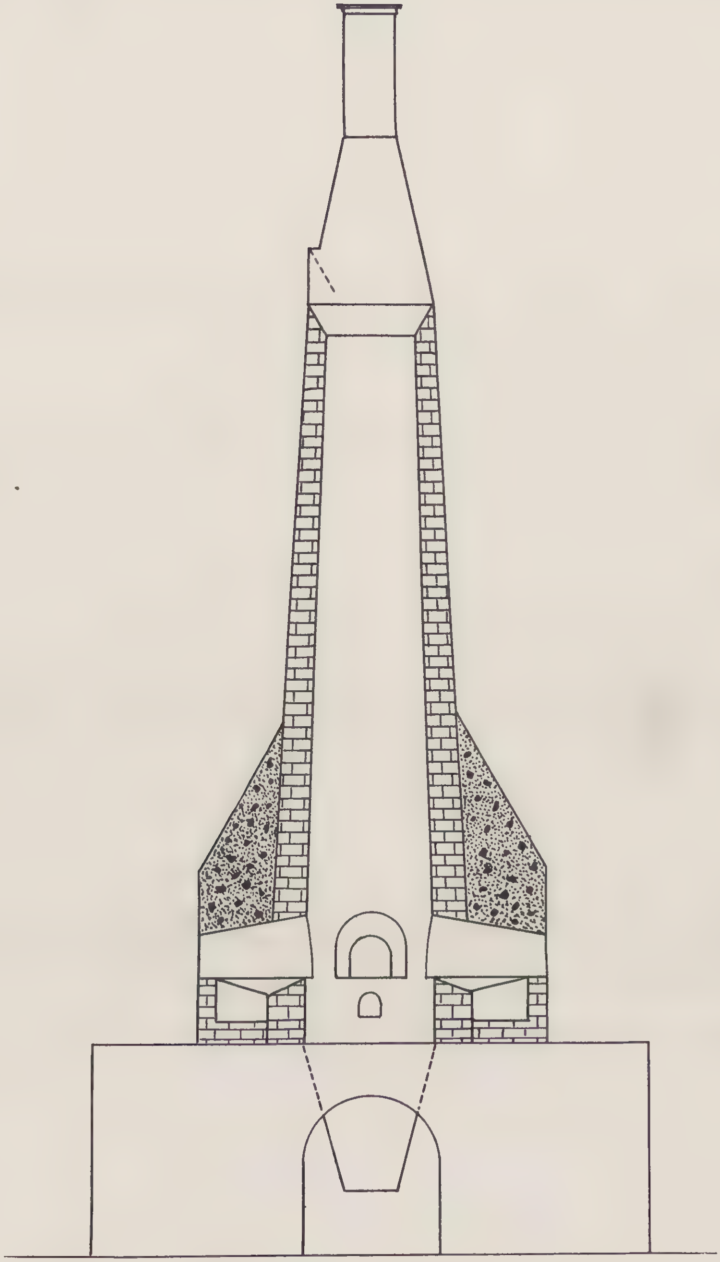
Draw Kiln

Described by Jackson in 1839



Vertical Steel Kiln

A Modern Steel Encased Flame Kiln.



Vertical Steel Kiln with Stack

A Modern Steel Encased Flame Kiln with Stack to Increase the Draught

The Aalborg or Schöfer kiln, neither of which has been much used in this country, illustrates the best development of this class of kiln. The stone is charged in at the top, while the fuel is fed into chutes, which join the main shaft of the kiln some distance below the top. Such kilns are very economical in fuel, but the lime is contaminated with the ashes.

VERTICAL STEEL KILN (b) *Vertical Kiln with Separate Feed*—This is the most common type of kiln at present used in this country. It consists of a vertical shaft built of masonry and lined with fire brick, having a round section. It is equipped with two or more fire boxes like Dutch ovens for burning the fuel which are built into the side of the kiln near the bottom so that the fuel does not come in contact with the lime. Its advantages are that any kind of fuel can be used including coal, wood, gas or oil, and the lime produced is clean because it does not come in contact with the burning fuel. Other things being equal, the fuel economy would not be so great as in class (a) above. Pages No. 28 and 29.

RING KILN (c) *Ring or Chamber Kiln*—This kiln is generally known as the Hoffman Kiln, and it has been extensively used for burning brick, cement and lime in Europe. It has been but little used in this country for burning lime, although there are now old kilns of this type at Riverton, Va. and Kelley Island, Ohio. It is very economical in fuel, producing a good grade of lime, but the labor cost of operating is excessive.

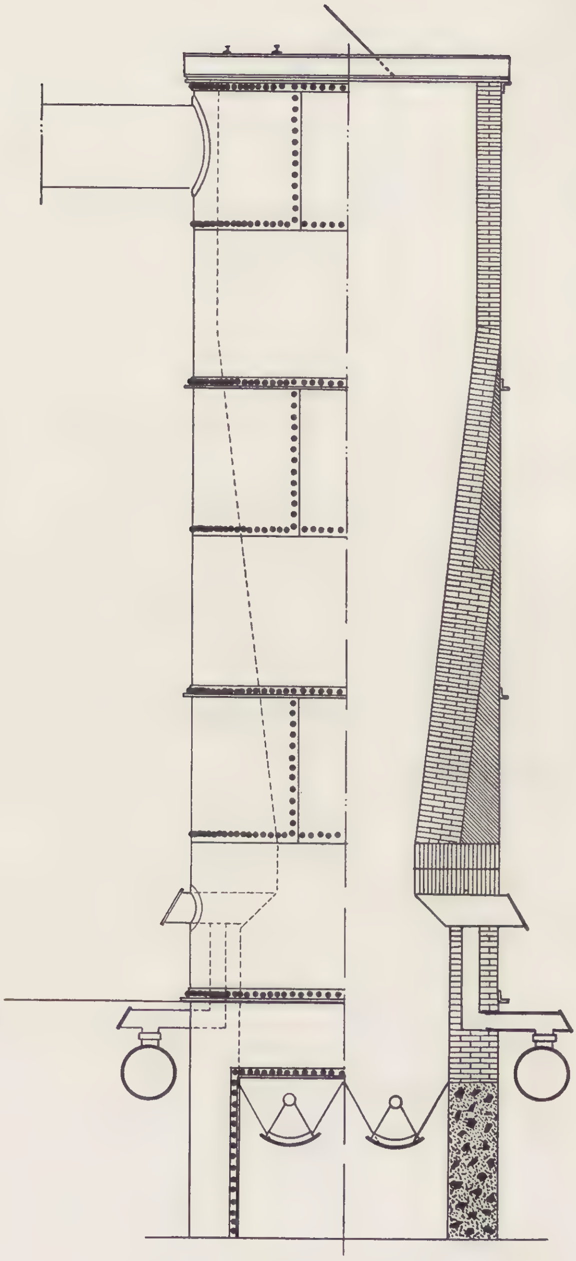
ROTARY KILN (d) *Rotary Kiln*—This kiln is the same as that commonly employed for burning Portland cement, except that gaseous fuel is used. The kiln is very economical both as to fuel consumption, and the cost of labor to operate. It has, however, the disadvantage that limestone fed to it must be crushed rather finely, and hence the burned product is also fine.

FUEL The use of kilns with separate fire boxes was largely brought about by the high cost of wood and the necessity of employing a cheaper fuel, such as coal. As long as wood was plentiful and cheap, it was the fuel most used for burning lime, and the simpler type of kiln was practical. With the increasing scarcity of wood, most lime plants have been forced to adopt the use of coal, and the use of coal has in turn necessitated the adoption of a different and more complicated type of kiln. If an old lime burner is asked "what is the best fuel for the burning of lime," his answer will be "wood," since wood produces a long, mild flame. Unless the combustion is carefully controlled when coal alone is used, there is undoubtedly too short and intense a flame to produce the best quality of lime.

Coal Methods of controlling the combustion have been devised so that there is obtained from coal the desired long, mild flame, which produces a good grade of lime. The most common of these methods is to introduce steam below the grates of the fire boxes. Another device is that known as the Eldred process. By this process a portion of the gas is removed from the kiln near the top by means of a fan, and this gas is then mixed with air and introduced beneath the grates of the furnace. This process accomplishes a dilution of the air by mixing it with the spent gas from the top of the kiln, and a good, long flame of low intensity is produced. This flame is not apt to overheat the lime nor cause overburning.

Producer Gas The most recent advance in connection with the use of coal is its gasification in producers, and the use of this gas to burn the lime. Producer gas gives a flame of low intensity and great volume which resembles closely the flame of burning wood. The producer gas method of burning requires more careful regulation and more skillful management than the other methods. A number of producer gas installations have proved failures because of the lack of knowledge as to how they should be installed and lack of scientific management. Pages No. 32 and 33.

It will thus be seen that from the simple kilns used by our forefathers in which wood was used as a fuel, we have advanced to a more complex type of kiln which resembles somewhat an iron blast furnace, and in which producer gas is used as fuel. With each step in the advance, the amount of capital required to construct the kiln has greatly increased.



Vertical Producer Gas Kiln

A Modern Producer Gas Fired Lime Kiln

Modern Installation of Lime Kilns Equipped to Use Producer Gas

SLAKING LIME

CHAPTER V

Chemical Change During Slaking Process The term "slaking" refers to the change produced when lime is treated with water. As is well known, a violent action occurs when water is added to lime: the lumps break up, heat is generated, and a product is formed which has an entirely different character than the original quick lime. This phenomenon indicates that a chemical reaction has taken place. In this chemical change the calcium oxide (lime) has united with water forming a new compound, calcium hydroxide (slaked lime). The chemistry of this change has been fully explained in the chapter devoted to the "Chemistry of Lime."

Quick or Slow Slaking Limes In order to render lime as it comes from the kiln suitable for use in mortar it is necessary to slake it. This is generally accomplished by adding sufficient water to the lime to produce a thick paste. The various kinds of lime mentioned under the chemical classification of lime act in very different manners when treated with water. The high calcium limes are quick slaking and give off the greater amount of heat because these limes consist principally of calcium oxide, this being the material which, by combining with water, generates the heat. As the amount of impurities (silica, alumina and iron oxide), increases the lime contains less calcium oxide and is therefore slower slaking. Such slow slaking limes are generally termed "lean" limes.

The dolomitic quick limes are slower slaking and generate less heat because they contain less calcium oxide; a part of the calcium oxide being replaced by magnesium oxide which does not combine with water under the ordinary conditions of slaking. In case the dolomitic limes contain impurities, such as silica, alumina and iron oxide, they are rendered slower slaking for the same reason as given for the high calcium lime.

Method of Slaking The ordinary method of slaking quick lime is to add sufficient water to produce a thick paste after the reaction of slaking is completed. In this method of slaking sufficient water should be used in order that it may come in contact with all parts of the lime. If insufficient water is used some parts of the mass of lime become dry and are "burned" in slaking. "Burned" lime works

tough and non-plastic in the mortar. If an excess of water is used, the slaking proceeds slowly and the resulting paste is thin and watery. Such lime paste is spoken of as "drowned."

Since various kinds of lime differ greatly in their behavior in slaking, some requiring more water and some a longer time to become reduced to a proper paste, it is necessary to exercise great care in slaking. A quick slaking lime will require a large amount of water and this must be added quickly, also the lime must be turned over rapidly so that the water has access to all parts and no "burning" takes place during slaking. On the contrary, the slower slaking limes, such as the dolomites, require less water, and care is necessary to see that these limes are not "drowned." In a treatise of this kind, it is impossible to give detailed instructions as to the best method of slaking the individual limes since each lime possesses its own characteristics, particularly as to its behavior in slaking. Too often the slaking is left to inefficient and ignorant labor with the result that the mass of lime is not thoroughly slaked, being either "burned" or "drowned."

Quantity of Water Required for Slaking Some recent tests made by Cloyd M. Chapman* illustrate very clearly the variation in the amount of water required to slake lime to a paste. In making this test great care was exercised to bring the paste to a standard uniform consistency.

TABLE No. 3—Results of Lime Tests

HIGH CALCIUM LIME

Sample No.	117	114	116	118	120	113	119	115	
Source	York Pa.	Farnum Mass.	Farnum Mass.	Rock-land Me.	West Stock-bridge Mass.	York Pa.	Adams Mass.	West Stock-bridge Mass.	
Marked	Lump Lime	Lump Lime	Lump Lime	Lump Lime	Lump Lime	Lump Lime	Granu-lar Lime	Lump Lime	Av.
Analysis CaO	99.04	98.91	98.91	96.81	95.23	95.00	94.87	84.31	95.38
MgO	0.65	.....	.....	1.27	0.71	.....	0.84	5.84	1.16
SiO_2	0.10	0.73	0.73	0.42	3.46	.....	2.05	3.54	1.38
R_2O_3	0.12	0.36	0.36	0.88	0.60	0.36	1.86	2.00	0.77
Gals. water per bbl. to make putty	29.4	32.2	32.7	30.5	32.4	29.1	32.9	28.3	30.9
Lbs. lime in 1 cu. ft. putty	43.1	38.7	38.0	44.6	41.2	41.8	38.6	45.2	41.4
Weight 1 cu. ft. putty in lbs.	95.2	93.0	89.3	100.1	96.7	92.2	91.5	97.8	94.4

*Data on Lime Putty and Cream of Lime by Cloyd M. Chapman, Journal of American Concrete Institute, November and December, 1914.

TABLE No. 3—Results of Lime Tests, Cont'd.
DOLOMITIC LIME

Sample No. / Source	121 Dover Plains N. Y.	124 Knicker-bocker Pa.	
Marked	Dutchess County Lime	Lump Lime	Average
Analysis CaO	56.46	56.99	56.72
MgO	38.54	40.11	39.32
SiO_2	1.58	2.11	1.85
R_2O_3	1.60	0.79	1.14
Gals. water per bbl. to make putty	25.3	22.8	24.0
Lbs. lime in cu. ft. putty	50.6	56.5	53.5
Weight 1 cu. ft. putty in lbs.	102.4	109.0	105.7

An inspection of Table No. 3 brings out the following features:

(1) The amount of water required to make putty by the dolomitic limes tested is about 20 per cent less than for the high calcium limes.

(2) The amount of water required to slake and reduce to a putty one barrel of high calcium lime is a variable quantity and for the samples tested ranges from 28.3 to 32.9 gallons. The average is about 31 gallons and for average conditions this figure may be close enough for most purposes. In the cases of the dolomitic lime this quantity of water is considerably less and averaged for the two samples tested 24 gallons.

(3) The weight of high calcium lime in a cu. ft. of putty ranged from 38.6 to 45.2 lbs. and averaged 41.4 lbs., which figure is probably a satisfactory one to use on the job. For dolomitic limes the average was 53.5 lbs.

(4) The weight of 1 cu. ft. of putty made from high calcium lime varied from 89.3 to 100.1 lbs. and averaged 94.4 lbs. and for dolomitic limes the average was 105.7 lbs.

In order to make this point more clear the table has been recalculated, allowance being made for the amount of water which enters into chemical combination with the lime.

HIGH CALCIUM LIME

Sample No.	117	114	116	118	120	113	119	115	Av.
Lbs. CaO in bbl. (185 lbs. lime net)	183.2	182.9	182.9	179.1	176.2	175.7	175.5	156.0	
Water chemically combined with lime, lbs.	58.8	58.7	58.7	57.5	56.6	56.5	56.4	50.1	
Free water in paste, lbs.	186.2	220.7	214.9	196.7	213.5	186.1	217.8	137.0	
Free water in paste, gals.	22.3	26.5	25.8	23.6	25.6	22.3	26.1	16.4	23.6

DOLOMITIC LIME

Sample No.	121	124	Av.
Lbs. CaO in bbls. (185 lbs. lime net)	104.4	104.9	
Water chemically combined with lime, lbs.	33.5	33.7	
Free water in paste, lbs.	177.2	146.2	
Free water in paste, gals.	21.2	17.5	19.3

The first line gives the number of pounds of calcium oxide in a barrel of lime containing 185 pounds net.

The second line gives the pounds of water chemically combined with the above amount of calcium oxide.

Line three gives the pounds of free water in the paste.

Line four gives the gallons of free water in the paste.

An inspection of this table shows that the amount of free water in a paste made from high calcium lime varies from 16.4 gallons to 26.5 gallons with an average amount of 23.6 gallons.

The amount of free water in a paste made from dolomitic lime varies from 21.2 gallons to 17.5 gallons with an average of 19.3 gallons.

The above two tables illustrate very clearly the great variation in the quantity of water required to reduce various limes to a workable paste. Because of this great variation, it is very difficult to determine in advance the amount of lime which is present in a mortar made from lump lime.

Lime "Burned" During Slaking It is a well known fact that when quick lime is slaked to a paste, if insufficient water is used the resulting paste is not so plastic and works short. This condition is generally spoken of as "burning" in slaking. Until very recently, no scientific reason was known for this "burning" of lime during slaking. W. E. Emley, of the U. S. Bureau of Standards, in a paper presented before the National Lime Manufacturers' Association in February 1914, gave the first explanation of this "burning" during slaking with which the writer is familiar. According to Emley, when insufficient water is used in slaking, the temperature of the mass is raised considerably above the boiling point of water, and at this elevated temperature a compound is formed which has different characteristics than ordinary calcium hydroxide. For convenience it may be called lime "burned" during slaking. This "burned" compound differs chemically from calcium hydroxide in the rapidity with which it absorbs carbon dioxide from the air, this reaction being so rapid that it is practically impossible to weigh the material on the ordinary chemical balance. Physically it differs from both lime and hydrate in that it feels gritty and has a slightly yellow color. Under the microscope it differs optically from both lime

and hydrate. These chemical and physical differences show that the compound formed by "burning" in slaking is neither lime nor hydrate but a new chemical compound. Since the material has not been isolated in a pure state it is therefore impossible to assign to it a definite formula; in all probability it is an oxy-hydrate. It has been shown that a basic carbonate of lime having the formula $2CaO.CO_2$ can be formed, also the corresponding hydrate is known $Ca(OH)_2.CaCO_3$. Arguing from these compounds, the probable formula for the so called oxy-hydrate would be $CaO.Ca(OH)_2$.

Aging Lime Paste The danger of "burning" in slaking is much greater with high calcium limes since these generate the greater amount of heat, and it is therefore necessary to employ a large excess of water and to see that all the lime comes in contact with water. This excess of water lowers the temperature both by absorbing the heat and by evaporation.

Slaking is a chemical process and time is required to complete the action; hence, it is necessary to allow the paste to age for some time to be assured of complete slaking. All lime contains some over-burned particles, or particles of lime which have united chemically with the silica or clay in the limestone, and these particles are extremely slow slaking, often requiring days and weeks to become thoroughly satisfied with water. Our forefathers recognized this fact and always allowed the lime paste to age for weeks, and often months, before using.

The necessity of aging lime paste before using was recognized by the Romans. Vitruvius gives the following directions for the preparation of lime paste to be used in plastering.* "This will be all right if the best lime, taken in lumps, is slaked a good while before it is to be used, so that, if any lump has not been burned long enough in the kiln, it will be forced to throw off its heat during the long course of slaking in the water, and will thus be thoroughly burned to the same consistency. When it is taken not thoroughly slaked but fresh, it has little crude bits concealed in it, and so, when applied, it blisters. When such bits complete their slaking after they are on the building, they break up and spoil the smooth polish of the stucco.

"But when the proper attention has been paid to the slaking, and greater pains have thus been employed in the preparation for the work, take a hoe, and apply it to the slaked lime in the mortar bed just as you hew wood. If it sticks to the hoe in bits, the lime is not yet tempered; and when the iron is drawn out dry and clean, it will show that the lime is weak and thirsty; but when the lime is rich and properly slaked, it will stick to the tool like glue, proving that it is completely tempered."

*Vitruvius, translated by Morris Hicky Morgan, Cambridge, Mass., 1914, page 204.

The art of preparing lime mortar of the finest quality has survived in Italy to this day. *"So late as 1851 an English architect, when sketching in the Campo Santo at Pisa, found a plasterer busy in lovingly repairing portions of its old plaster work, which time and neglect had treated badly, and to whom he applied himself to learn the nature of the lime he used. So soft and free from caustic qualities was it that the painter could work on it in true fresco painting a few days or hours after it was repaired, and the modeler used it like clay. But until the very day the architect was leaving no definite information could he extract. At last, at a farewell dinner, when a bottle of wine had softened the way to the old man's heart, the plasterer exclaimed, 'And now, signor, I will show you my secret!' And immediately rising from the table, the two went off into the back streets of the town, when, taking a key from his pocket, the old man unlocked a door, and the two descended into a large vaulted basement, the remnant of an old palace. There amongst the planks and barrows, the architect dimly saw a row of large vats or barrels. Going to one of them, the old man tapped it with his key; it gave a hollow sound until the key nearly reached the bottom. 'There, signor! There is my grandfather! He is nearly done for.' Proceeding to the next, he repeated the action, saying, 'There, signor, there is my father! There is half of him left.' The next barrel was nearly full. 'That's me!' exclaimed he; and at the last barrel he chuckled at finding it more than half full; 'That's for the little ones, signor!' Astonished at this barely understood explanation, the architect learned that it was the custom of the old plasterers, whose trade descended from father to son from many successive generations, to carefully preserve any fine white lime produced by burning fragments of pure statuary, and to each fill a barrel for his successors. This they turned over from time to time, and let it air-slake in the moist air of the vault, and so provide pure old lime for the future by which to preserve and repair the old works they venerated. After inquiries showed that this was a common practice in many an old town, and thus the value of old air-slaked lime, such as had been written about eighteen hundred years before, was preserved as a secret of the trade in Italy, whilst the rest of Europe was advocating the exclusive use of newly burnt and hot slaked lime."

Necessity for Hydrated Lime If a good, sound, smooth working lime paste is to be made from lump lime, it is absolutely necessary that the lime be slaked some considerable time before using. Compare the method of slaking recommended by Vitruvius and that of the skilled Italian plasterer with the modern method of slaking the lime in the middle of a ring of sand and almost immediately hoeing in

*Hodgson, Concrete, Cement, Mortar, Plaster and Stucco, pages 22 to 25.

the sand. In the present practice more often than not, the plaster is placed on the wall or the mortar laid between the bricks within a few hours. Such mortar must contain free lime that has not had time or opportunity to slake. This lime later takes up water causing the mortar to be crumbly or the plaster to crack and pop.

In spite of improvements in the method of producing lime with better and more economical kilns, the material is brought into the market in the same manner as it was centuries ago. Further, the method of slaking lime has changed only for the worse, in that our rapid modern practice does not admit of the slow action of slaking lime thoroughly on the operation.

The only improvement in the form of the merchantable lime, known to the author, is that of hydrated lime. This will be dealt with in the next chapter.

MANUFACTURE OF HYDRATED LIME

CHAPTER VI

WITHIN recent years a method has been introduced of treating lime with water in a suitable apparatus in which the lime combines with sufficient water to satisfy the chemical requirements of the calcium oxide forming a dry, finely divided flour, the so called Hydrated Lime. *Hydrated lime can be defined as the dry flocculent powder resulting from the treatment of quick lime with sufficient water to satisfy the calcium oxide.* This material comes into the market in bags or other convenient packages and is ready for use requiring only gauging with water and mixing with sand in much the same manner as cement is used. The fact that lime could be slaked to the form of a dry powder has long been known, and three methods have been used in the past to produce this powder.

METHODS OF DRY SLAKING

1. Lime, in comparatively small pieces about the size of an egg, is placed in a basket and immersed in water for a minute or two until hydration has commenced, when it is withdrawn. The wet lime is generally put in heaps or silos in order to conserve the heat and prevent the escape of the vapor. The material swells, cracks and becomes reduced to a dry powder.

2. Lumps of lime are placed in a heap and wetted at intervals so that the mass is equally moistened throughout. The slaking proceeds as in the first instance.

3. Small pieces of lime are exposed to the air for a number of months. The material absorbs both water and carbon dioxide from the atmosphere, falling to a dry powder. The powdered form consists of a hydrated sub-carbonate of lime containing about 10% to 11% of water.

These methods of dry slaking lime are crude, and unless the greatest care is exercised, the resulting dry product will contain particles of unslaked lime. Further, the hydrates produced by these methods generally work short and possess poor sand carrying capacities; in fact, hydrated lime produced by any of the above methods is only suitable for use on the soil, and such hydrate should not be confounded with hydrated lime manufactured by modern methods.

Modern Methods of Hydrating The modern method of manufacturing hydrated lime depends upon the addition of an exact amount of water to a pre-determined exact amount of lime. By no other method is it possible to produce a hydrate which will contain sufficient combined water to satisfy the demands of the calcium oxide present. It is important that all the calcium oxide be in combination with water, otherwise the hydrate will be unsound and unsuitable for many uses. This point will be insisted upon in any specifications that may be drawn for hydrated lime to be used in the building trade. It is vital for each manufacturer to recognize the fact that the formation of hydrated lime involves a chemical change, requiring the presence of definite amounts of lime and water. Since the process is chemical, it requires the same careful supervision as any other chemical process, such as the manufacture of Portland cement.

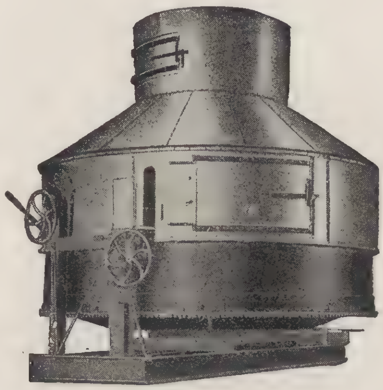
Pierce Process The first commercial process used for preparing hydrated lime in this country was the so-called "Pierce" Process. This consisted in slaking the lime to a wet paste, then drying the paste so as to expell all the excess moisture over and above that needed for the chemical requirements, thereby reducing the material to a form that could be ground. If the process was carefully carried out, a good grade of hydrated lime was produced. This method has been abandoned owing to the excessive cost of manufacture.

Dodge Process The second method employed was the so-called "Dodge" Process. This process consisted first in grinding the lime so as to pass a 26 mesh sieve, second in treating a weighed amount of the ground lime with sufficient water thoroughly to satisfy the calcium oxide present and produce a dry hydrate, third the dry hydrate was sifted through fine silk cloth. A description of this method is given in the "Engineering News," Vol. 50, Pages 177 to 179, August 27, 1903, by S. Y. Brigham. In this article it is stated that on the average high calcium limes containing 97% of calcium oxide require about 55 pounds of water to 100 pounds of lime, while dolomitic limes require only 36 pounds of water to 100 pounds of lime to produce a good hydrate.

From these two pioneer processes have been evolved, during the last fifteen years, the methods described below which are in use at the present time.

Clyde Process A weighed quantity of ground lime is fed from a hopper directly into a large horizontal pan. This pan is so mounted that it can be rotated around its vertical axis, and there are a series of plows arranged to turn over and mix the material in the pan. To the weighed amount of lime a pre-determined quantity of water is

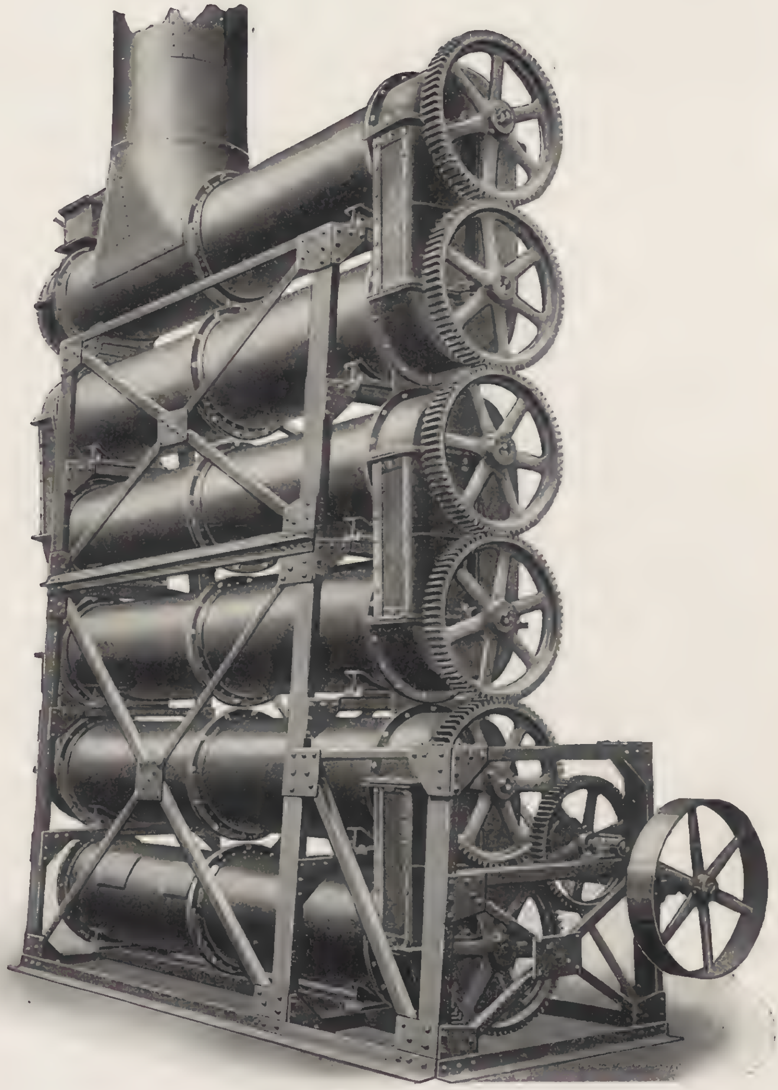
added and the whole mass agitated by revolving the pan. When all the water needed chemically, has been taken up, and the excess driven off as steam, the hydrated lime is dumped through an opening in the centre of the pan. It is customary to take the hydrate directly from the pan, and store it in bins in order to age the product. The dry hydrate from the bins is either screened or graded by means of air separation.



CLYDE HYDRATOR

REANEY PROCESS A weighed amount of the lime is introduced into the upper end of a cylinder, which is slightly inclined from the horizontal. A sufficient amount of water is added, and the material agitated by revolving the cylinder. Inside of the cylinder there are a series of encircling rings, which act as dams to retard the flow of the lime toward the discharge end. The lighter particles of the hydrate rise and pass over the retarding rings while the heavier, unhydrated particles are retained until the hydration is complete. The lower or discharge end of the cylinder is encircled with a tapering screen; the fine hydrated particles pass through this screen, and are removed. The coarser particles which pass over the screen, are either thrown away or returned to the feed end of the hydrator for further treatment.

KRITZER PROCESS The cracked or ground lime and water are separately fed into the upper of a series of enclosed cylinders (generally 4 or 6) mounted one on top of the other. The amount of lime is controlled by a screw feeding device and the quantity of water is proportioned by a needle valve. The lime and water are propelled throughout the series of cylinders by means of paddles mounted on a shaft extending through each cylinder; these shafts being rotated by gearing on the outside. Both materials are thus carried through the whole series of from four to six cylinders, and the product is discharged from



Kritzer Hydrator

the lower or last cylinder thoroughly hydrated. The machine is also provided with a stack on the upper cylinder, and openings in the lower cylinder, thus a draft is produced through the cylinders in the opposite direction to the travel of the lime.

Lauman Process The cracked lime is fed directly into an inclined stationary cylinder; within this cylinder are paddles carried on a shaft which feed the lime forward by their revolutions. The water is added through a pipe in the upper end of the cylinder. As the material is gradually fed forward it becomes mixed with water and the hydration takes place. The quality of the hydrate is judged by observing the material discharged from the cylinder.

These methods are in commercial use today and a good grade of hydrate can be produced by any of the methods provided sufficient care is taken to assure the addition of the correct amount of water and sufficient time is allowed to form a sound hydrate. It is the general custom either to screen the hydrate or to pass it through an air separating system in order to remove particles of unhydrated lime, core and other impurities. It is further important that the heat generated by the action of the lime and water, be removed as rapidly as possible in order to keep the temperature of hydration below the point at which the lime "burns" in slaking.

Important Features in Hydrating In any method of hydrating lime an excess of water is used over and above that required to combine chemically with the lime. This excess water is driven off as steam by the heat generated in slaking. The quantity of water required is subject to wide variations, since it is dependent upon a number of conditions, such as the temperature of the water, lime and the atmosphere. If too little water is used, some particles of lime will not have access to water and these will not slake but will be present in the finished hydrate, causing it to be unsound. Also too little water results in the production of a hydrate which works short, due to its having been "burned" in slaking. Too much water results in a damp or wet hydrate, which is difficult to handle. The addition of the correct amount of water requires the most careful supervision of any of the operations of hydration if a good grade of hydrate is to be produced. This part of the operation must be carefully controlled and be subjected to checks from day to day.

PROPERTIES OF HYDRATED LIME

CHAPTER VII

Water Content in Hydrated Lime Hydrated lime is a fine dry powder consisting essentially of calcium hydrate and magnesium oxide. The amount of combined water contained in the hydrate varies directly as the calcium oxide content. Since calcium oxide is the only compound present in lime which possesses the property of combining with water, it follows that the greater the amount of calcium oxide present in the lime, the greater will be the amount of water required to combine with it. A more complete explanation of this fact has been given in the chapter devoted to the Chemistry of Lime.

This is illustrated by the table given below:

Percent of calcium oxide in original lime		Percent of calcium oxide in hydrate	Percent of water required in hydrate
100	(a)	75.675	24.325
95	(b)	72.78	23.08
58.34	(c)	49.12	15.78
52	(d)	44.55	14.33

(a)—Pure high calcium lime
(b)—High calcium lime 5% impurities
(c)—Pure dolomitic lime
(d)—Impure dolomitic lime

Pure high calcium hydrate contains 24.32% of combined water, while a pure dolomitic hydrate contains only 15.78%. As the amount of impurities (silica and clay) increases, the amount of combined water decreases. This may be seen by comparing (b) with (a) and (d) with (c) in the above table.

Chemical Composition of Various Hydrated Limes The chemical compositions of various commercial hydrated limes are given below:

No.	1*	2*	3*	4*	5**	6*	7*
Silica	.42	.97	.95	1.23	.96	3.05	.24
Alumina	.....	.29	.50	.42	.63	.20	.22
Iron Oxide	.21	.33	.51	.18	.13	.30	.06
Lime	72.25	69.63	71.66	71.22	73.45	48.76	52.27
Magnesia	1.47	4.11	.36	1.88	.58	30.04	28.96
Carbon Dioxide	.57	1.88	1.80	1.37	.69	.92	.....
Water	24.98	22.56	23.81	23.76	23.97	16.32	16.79
Combined Oxides CaO+MgO (Calculated)	73.72	73.74	72.02	73.10	74.03	78.80	81.23

1—Maine 3—Pennsylvania 5—Washington 7—Ohio
2—New Jersey 4—Alabama 6—Michigan

Numbers 1, 2, 3, 4 and 5 represent high calcium hydrate.
Numbers 6 and 7 represent dolomitic hydrate.

*Analyses from Technologic Paper No. 16, Manufacture of Lime, Bureau of Standards.
**Analysis by Author.

Physical and Chemical Characteristics In 1909 the author gave a table showing the most important chemical and physical characteristics of hydrated lime to the National Lime Manufacturers' Association. This table is here reproduced.

	Dolomitic Hydrates				High Calcium Hydrates	
1—Weight per cu. ft. loose	30.40	31.72	37.20	36.30	35.70	35.80
2—Weight per cu. ft. shaken	36.40	36.23	42.40	45.10	41.20	45.30
3—Specific Gravity	2.50	2.53	2.41	2.50	2.16	2.07
4—Residue Insoluble in hydrochloric acid	.40%	.40%	.24%	.28%	.25%	.33%
5—Moisture	.30	.00	.35	.00	.00	.00
6—Combined water	17.22	15.88	18.07	17.29	24.52	24.37
7—Carbon Dioxide	.75	.30	.41	.17	.54	.15
8—Available Oxide	80.38	83.02	80.47	82.03	74.00	74.96

Referring to the table, the horizontal line 1 gives the weight per cubic foot, loose.

Line No. 2 gives the weight per cubic foot, shaken.

Line No. 3 gives the specific gravity—this is obtained by dividing the weight of the substance by the weight of the same volume of water. It is, therefore, a measure of density, and gives the relative weight of the unit volume of the material as compared to the weight of unit volume of water. The higher specific gravity of the dolomitic hydrate is due to the fact that only the lime present in the calcined dolomite combines with water, the magnesia being present as the oxide. From the specific gravity and the weight per cubic foot of any material it is possible to calculate the amount of voids or the space occupied by the air. Assume the specific gravity of a hydrate to be 2.50 and the weight to be 40 lbs. to the cubic foot. The specific gravity means that a cubic foot of perfectly solid hydrate weighs 2.50 times as much as a cubic foot of water. A cubic foot of water weighs 62.4 lbs., then a cubic foot of hydrate (perfectly solid containing no voids) would weigh $62.4 \times 2.50 = 156$ lbs. The hydrate, however, weighed only 40 lbs. per cubic foot, therefore the air occupied a space equal to such a volume of hydrate as would weigh $(156-40=116)$ 116 lbs. The per cent of voids would be $116/156 = 74.4\%$.

Line No.4 is the residue insoluble in dilute hydrochloric acid (muriatic acid) and consists of sand, clay, or ashes present in the hydrated lime. In every case (except in hydraulic hydrates) this is inert material and has no value as a binding agent; it should, therefore, be looked upon as an impurity and in case the amount is over 2% it would materially injure the sand carrying capacity of the hydrate.

Line No. 5 gives the amount of water present as free (or mechanically contained) moisture and not combined with the lime. This should be present only in small quantities. If too great an excess of water is present the hydrate will have a tendency to lump or cake.

Line No. 6 gives the amount of water which has entered into chemical combination with the lime to form the hydrate and which is a necessary and important ingredient. The amount should always be sufficient to satisfy all the calcium oxide present. Attention has been called to the fact that the amount of combined water is always greater in the high calcium hydrates.

Line No. 7 gives the carbon dioxide (carbonic acid gas) present in the hydrate. This gas is in combination with the lime and denotes either the presence of unburned limestone (core) or that the hydrate has taken up carbonic acid from the atmosphere; in any case the amount present should be small, less than 2%, otherwise it indicates an inferior hydrate. The lime already combined with carbonic acid is inert and unable to contribute any strength to the mortar.

Line No. 8: in this horizontal line the amount of caustic oxides present has been calculated, that is, the amount of bonding material which is capable of uniting with the carbonic acid of the atmosphere thereby producing the bond of the mortar. This is deduced by subtracting from 100 the residue insoluble in hydrochloric acid (4), moisture (5), combined water (6) and the amount of calcium carbonate corresponding to the amount of carbonic acid present in the hydrate $\left\{ \frac{(7) \times 100}{44} \right\}$

The numbers in parenthesis refer to the horizontal lines in the preceding table.

USE OF HYDRATED LIME IN SAND MORTARS

CHAPTER VIII

IT may be stated that hydrated lime is suitable for any use in the building trade to which lump lime can be put. This in general includes its use in mortars and plasters and it would appear that as the material becomes better known, its advantages will be found to outweigh any disadvantages.

A mortar made with hydrated lime often does not trowel quite so easily as a mortar made from lime putty. The smooth working qualities of the hydrate can be greatly improved by proper method of manufacturing and by allowing the mortar or paste to soak over night so that the gauging water becomes thoroughly incorporated. The great ease of handling hydrate and the thoroughness with which it has been slaked make up to a great extent for any lack of plasticity.

The use of hydrated lime does away with the necessity of slaking lime to a paste, thus saving the cost of slaking. It is estimated that it costs 25 cents a barrel to slake lime in a mortar box. Hydrated lime comes into the market in convenient packages of a definite weight. This makes it possible to proportion the mortar so as to have exact quantities of lime and sand present, a fact which is always appreciated both by the architect and engineer. It is much more difficult to obtain accurate proportions of lime and sand when lump lime is used, especially as it is a general custom to add as much sand as possible with the result that the mortar is often over-sanded and possesses little strength.

ADVANTAGES OF HYDRATED LIME

In June, 1910, the author presented the results obtained from an extended series of tests on mortars made from both hydrated and lump lime, to the American Society for Testing Materials.* One of the most important conclusions drawn from these investigations was that the mortar produced from hydrated lime was stronger than that produced from the corresponding lump lime slaked to a paste. This conclusion was to be expected, since it is possible to manufacture hydrated lime by mechanical means under good chemical control, which is more thoroughly slaked than it is possible to slake lump lime on the job. The user in dealing with hydrated lime is handling a product which can be definitely proportioned and will

*Proceedings American Society for Testing Materials, 1910.

produce known results. The quality of hydrate desired can be specified in advance and the material can be inspected and tested (see specification for hydrate, page 84) in order to determine if it fulfills the requirements. The quality of quicklime can also be specified and its character determined by tests, but such tests do not indicate what will be the quality of mortar found on the job, since lime is chemically changed during slaking. Hydrated lime undergoes no further change upon the addition of water, therefore the same material is tested which is to be used. The testing of hydrated lime is no more difficult than the testing of cement. With lump lime the user is dependent always upon the thoroughness of slaking and it is well known that unless the paste is run off and stored for some considerable time, there is no assurance of complete and thorough slaking.

Practically all those who investigated the strength of lime mortars have recommended the use of hydrated lime rather than lump lime. In Circular No. 30, 1911 of the Bureau of Standards, the following statement is made: "The proportion of impurities in hydrated lime is generally less than that in the lime from which it is made. In building operations hydrated lime may be used for any purpose in place of lump lime, with precisely similar results. The consumer must pay the freight on a large amount of water, but the time and labor required for the slaking is eliminated and there is no danger of spoiling it either by burning or incomplete slaking * * *. For all building purposes hydrated lime is to be preferred to lump lime. By its use the time and labor involved in slaking may be saved and the experience of the laborer is eliminated as a factor in the problem." From the above it will be seen that those who have carefully investigated hydrated lime are firm in their opinion that it is safer and superior to lump lime.

In the past when lump lime was used almost exclusively for plastering, it was the practice to slake the lime and allow it to season for some considerable time before using in order that the plaster should contain no particles of quicklime. This occasionally caused delay in the construction of buildings. Moreover, plaster made from lime does not set quite so rapidly or in the same manner as gypsum plaster. These two points have led people to believe that buildings plastered with hydrated lime are delayed in the course of construction. By the use of hydrated lime the delay due to slaking and seasoning is done away with, and by a proper method of planning and rotating the work, the job can be completed without delay.

Second National Bank Building, Toledo, Ohio
D. H. Burnham & Co., Chicago, Ill., Architects
Hydrated Lime Plaster Used Throughout for Scratch, Brown and Finish Coats

Selection of Sand In the preparation of mortar or plaster, generally little attention is paid to the quality of the sand employed. Since the sand forms three-quarters or more of the mortar, it follows that the strength is largely dependent upon the quality of the sand used. Sand for use in lime mortars should be clean, free from dirt and loam, and as coarse as is consistent with the character of surface desired.

Investigations of sands have shown that coarse sand yields a stronger mortar than fine sand. It is better to use as coarse sand as possible if a strong mortar is desired. This is particularly the case in mortars used in brick work where the joints between the bricks are wide. The gradation of the sand grains, that is, the amount of the different sized grains present, should be such as to give the greatest density or the least voids in the sand. The following specifications for a mortar sand are taken from Bulletin No. 70, University of Illinois:

"The sand shall consist of grains of hard, tough, durable rock and must be free from soft, decayed or friable material.

"The suspended matter shall not exceed 6% by weight.

"Not more than 15% by weight, including the suspended matter, shall pass a No. 100 screen nor more than 80% a No. 16 screen.

"The voids shall not exceed 35% of the total volume."

Sand-Carrying Capacity of Hydrated Lime The statement is often made that hydrated lime will not carry so much sand as lime paste. This is really not the case. It is not to be expected that 200 pounds of hydrated lime will carry as much sand as 200 pounds of lump lime slaked to a paste for the simple reason that 200 pounds of hydrate contains less calcium and magnesium oxides than the paste resulting from slaking 200 pounds of lump lime. By referring to the equation for slaking lime on page 15, it will be seen that 56 pounds of pure high calcium lime gave 74 pounds of hydrate; therefore, 200 pounds of lime would give ($56:74 = 200:X$) 264 pounds of dry hydrate. Thus 264 pounds of hydrated lime contains the same amount of calcium and magnesium oxide as 200 pounds of lump lime slaked to a paste. It would require 264 pounds of hydrate to carry the same amount of sand as 200 pounds of lump lime.

Machine Mixed Mortar Within the last few years machines have been placed on the market to mix the sand and lime, these machines being similar in operation to a concrete mixer. By the use of such machines, it is possible to mix the lime and sand more thoroughly and the mixing is accomplished in less time than is required by hand. Hydrated lime is especially adapted for use in the mortar mixer because the material comes on the work in a convenient form and in packages of known weight.

On a recent job with which the author is familiar, all the mortar used in the brick work was mixed in this manner. The mixing machine was operated only during the last few hours in the afternoon, enough mortar being prepared for next day's requirements. The mortar mixed in the machine was dumped into the basement in a pile and was allowed to age over night. When used the mortar was entirely satisfactory and worked free and smooth.

Proportions of Materials Below are indicated the approximate proportions of hydrate and sand to be employed in mortar for various uses. It is not possible to give specifications covering all conditions, since different hydrates will carry varying quantities of sand and more particularly because the character of the sand materially influences the quantity of hydrate required.

PROPORTIONS FOR HYDRATED LIME PLASTER*

WOOD LATH—THREE COAT WORK

The following are the proportions in which materials should be mixed at the mixing plant or by the contractor on the job:

Per ton of Sanded Plaster	Per Hundred Pounds of Hydrated Lime
SCRATCH COAT	
1550 pounds sand	350 pounds sand
450 pounds hydrated lime	100 pounds hydrated lime
$3\frac{1}{2}$ pounds hair	$\frac{3}{4}$ pound hair
BROWN COAT	
1600 pounds sand	400 pounds sand
400 pounds hydrated lime	100 pounds hydrated lime
$1\frac{1}{2}$ pounds hair	$\frac{3}{8}$ pound hair

FINISH COAT, WHITE

Lime putty properly gauged with Plaster of Paris

SAND FLOAT FINISH	
1450 pounds sand	275 pounds sand
550 pounds hydrated lime	100 pounds hydrated lime

*These are average mixtures for first class, clean, sharp plastering sand. Mixtures may be changed to meet other qualities of sand.

WOOD LATH—TWO COAT WORK

Per Ton of Sanded Plaster	Per Hundred Pounds of Hydrated Lime
FIRST COAT	
1550 pounds sand	350 pounds sand
450 pounds hydrated lime	100 pounds hydrated lime
3½ pounds hair	¾ pound hair

FINISH COAT, WHITE

Lime putty properly gauged with Plaster of Paris

SAND FLOAT FINISH	
1450 pounds sand	275 pounds sand
550 pounds hydrated lime	100 pounds hydrated lime

METAL LATH—THREE COAT WORK

Per Ton of Sanded Plaster	Per Hundred Pounds of Hydrated Lime
SCRATCH COAT	
1550 pounds sand	350 pounds sand
450 pounds hydrated lime	100 pounds hydrated lime
4 pounds hair	1 pound hair
BROWN COAT	
1600 pounds sand	400 pounds sand
400 pounds hydrated lime	100 pounds hydrated lime
1½ pounds hair	½ pound hair

FINISH COAT, WHITE

Lime putty properly gauged with Plaster of Paris

SAND FLOAT FINISH	
1450 pounds sand	275 pounds sand
550 pounds hydrated lime	100 pounds hydrated lime

BRICK OR TILE—THREE COAT WORK

Per Ton of Sanded Plaster	Per Hundred Pounds of Hydrated Lime
SCRATCH COAT	
1600 pounds sand	400 pounds sand
400 pounds hydrated lime	100 pounds hydrated lime
1½ pounds hair	⅜ pound hair
BROWN COAT	
1600 pounds sand	400 pounds sand
400 pounds hydrated lime	100 pounds hydrated lime

FINISH COAT, WHITE

Lime putty properly gauged with Plaster of Paris

SAND FLOAT FINISH	
1450 pounds sand	275 pounds sand
550 pounds hydrated lime	100 pounds hydrated lime

BRICK or TILE—TWO COAT WORK

Per Ton of Sanded Plaster	Per Hundred Pounds of Hydrated Lime
FIRST COAT	
1600 pounds sand	400 pounds sand
400 pounds hydrated lime	100 pounds hydrated lime
1½ pounds hair	⅜ pound hair

FINISH COAT, WHITE

Lime putty properly gauged with Plaster of Paris

SAND FLOAT FINISH

1450 pounds sand	275 pounds sand
550 pounds hydrated lime	100 pounds hydrated lime

ON CONCRETE

100 pounds sand
800 pounds hydrated lime
250 pounds calcined plaster

WOOD LATH, BRICK OR TILE—ONE COAT WORK

1550 pounds sand
450 pounds hydrated lime
3½ pounds hair

GYPSUM BLOCK—THREE COAT WORK

Use the same quantities as shown for Brick or Tile.

NOTE—Mixtures specified on pages 53, 54 and 55 are average mixtures for first class, clean, sharp plastering sand. Mixtures may be changed to meet other qualities of sand.

HAND MIXED MORTARS In preparing these mortars, the best and most economical results will be obtained by the use of a mortar mixing machine, several of which are on the market. If hand mixing is to be used, two methods may be employed in preparing the mortar.

FIRST—Soak the hydrate with water so as to produce a thick paste, and allow to stand over night, then add the desired amount of sand and sufficient water to give the required consistency to the mortar. It is generally conceded that this method produces the more plastic mortar.

SECOND—Mix the hydrate and sand dry, the same as with cement mortar, then add the water to produce the required consistency.

When hair is used, it should always be well soaked and beaten before mixing with the mortar. Thorough hoeing and mixing always improves the plasticity and working qualities of a mortar.

LIME-CEMENT MORTARS

In many cases where a mortar having a greater strength is required, or it is advisable to have considerable strength produced quickly, it is advantageous to use Portland cement in the mixture.

Investigations by various authorities have proven the fact that hydrated lime and Portland cement can be mixed in any proportions from an addition of 10% of hydrate to the Portland cement for making a cement mortar to an addittion of 10% of Portland cement to the hydrate for making a hydrated lime mortar. The addition of hydrated lime to a cement mortar improves the plasticity and water tightness, and the addition of Portland cement to a hydrated lime mortar increases the early time strength.

Strength of Cement-Lime Mortars

From the results obtained by many investigations it may be stated that the replacement of 25% of Portland cement with hydrate in mortar does not materially weaken the mortar. Mr. Emley* from his investigation drew the following conclusion:

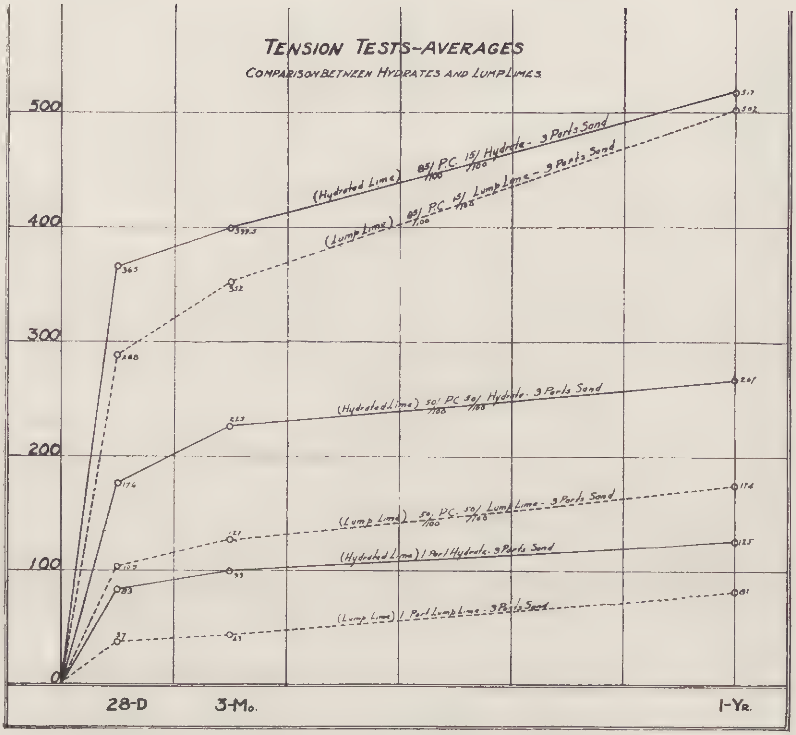
"1. While the strength does decrease with increasing proportions of lime, samples containing 25% lime are not very much weaker than those made of cement. 2. High calcium lime sets more rapidly than dolomitic lime. Specimens containing the former are therefore stronger when 7 days old. Those containing dolomite were almost as strong at 28 days and at 3 months had just about caught up to the high calcium limes. 3. Samples stored under water set more slowly than those stored in air, and were therefore weaker at 7 days. But at 3 months those stored under water were much the stronger, frequently showing twice the strength of the specimens stored in air. This applies equally to all specimens containing 25% or less of lime, whether dolomitic or high calcium."

Following will be found the results obtained from an extended series of tests made under the direction of Prof. Ira H. Woolson of Columbia University, N. Y.**

The charts on pages 57 to 60 clearly illustrate the greater strength developed by mortars made with hydrated lime over those made from the corresponding quick lime slaked to a paste. The curves plotted were obtained by averaging the results on similar tests of three different hydrated limes and three different quick limes.

*The use of hydrated lime in a Portland cement mortar, by Warren E. Emley and H. P. Greenwald, Proceedings, National Lime Manufacturers Association, 1913.

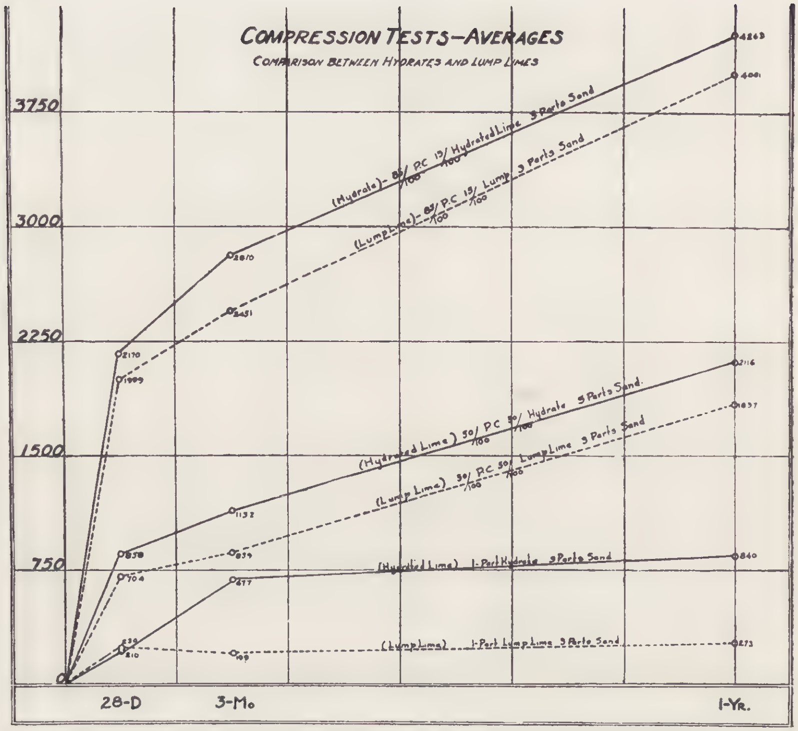
**Comparative Test of Lime Mortar, both in tension and compression, by E. W. Lazell, Proceedings of American Society for Testing Materials, Page 328, 1910.



Tension Tests Average, 1 to 3 Mixture.

	.85 Cement, .15 Lime, 3 Sand.		.50 Cement, .50 Lime, 3 Sand.		1 Lime, 3 Sand.	
	Quick-lime.	Hy-drate.	Quick-lime.	Hy-drate.	Quick-lime.	Hy-drate.
28 days......	288	365	103	176	37	83
3 months....	352	399.5	127	225	43	99
12 months....	502	517	174	267	81	125

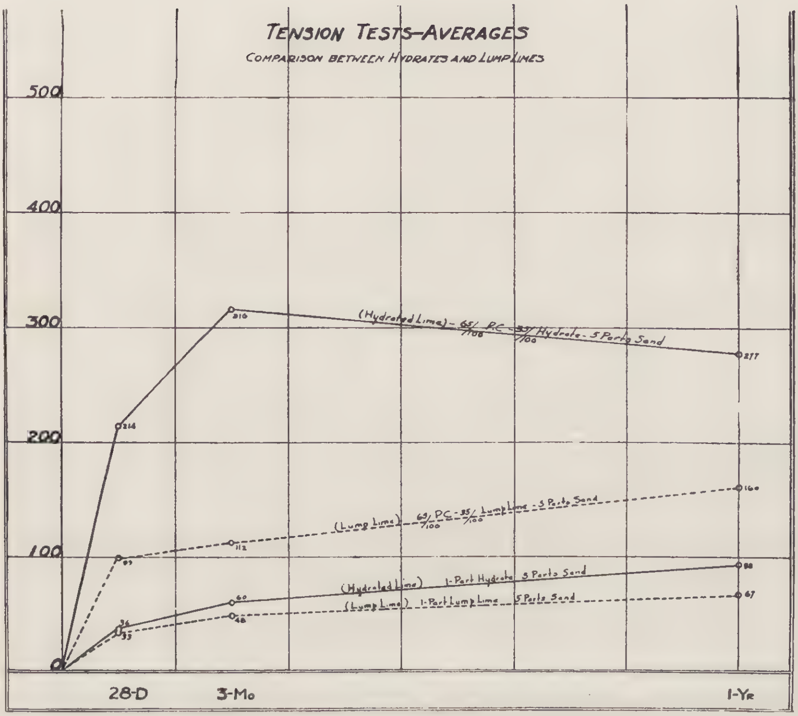
Percentage of Hydrated Lime is by weight of Portland cement



Compression Tests Average, 1 to 3 Mixture.

	.85 Cement, .15 Lime, 3 Sand.		.50 Cement, .50 Lime, 3 Sand.		1 Lime, 3 Sand.	
	Quick-lime.	Hy-drate.	Quick-lime.	Hy-drate.	Quick-lime.	Hy-drate.
28 days......	1,999	2,170	704	858	230	210
3 months....	2,451	2,810	859	1,132	199	677
12 months....	4,001	4,263	1,837	2,116	273	840

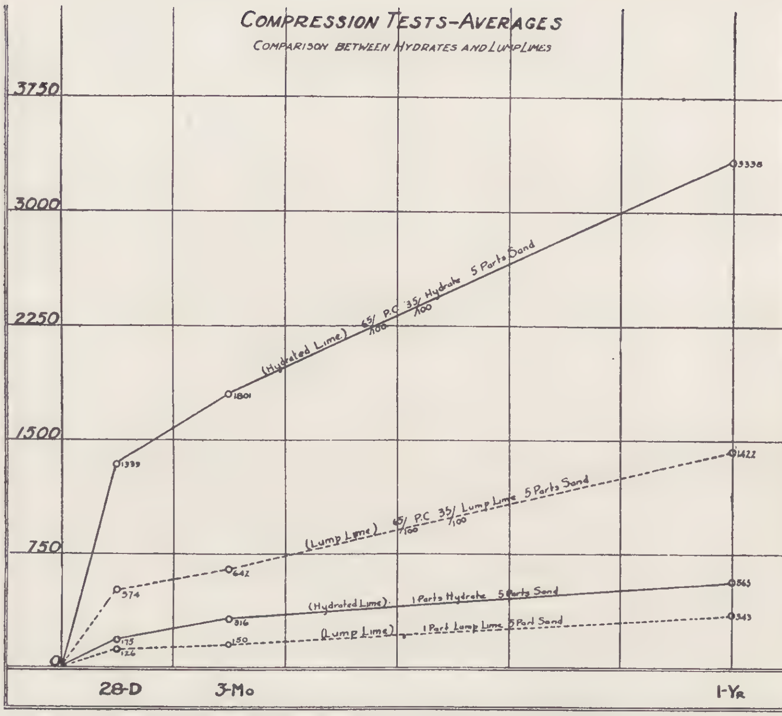
Percentage of Hydrated Lime is by weight of Portland cement



Tension Tests Average, 1 to 5 Mixture.

	65 Cement. .35 Lime. 5 Sand.		1 Lime, 5 Sand.	
	Quicklime.	Hydrate.	Quicklime.	Hydrate.
28 days	99	214	33	36
3 months	112	316	48	60
12 months.	160	277	67	93

Percentage of Hydrated Lime is by weight of Portland cement



Compression Tests Average, 1 to 5 Mixtures.

	.65 Cement, .35 Lime. 5 Sand.		1 Lime, 5 Sand.	
	Quicklime.	Hydrate.	Quicklime.	Hydrate.
28 days	574	1,339	126	175
3 months............	642	1,801	150	316
12 months............	1,422	3,338	343	565

Percentage of Hydrated Lime is by weight of Portland cement

Equitable Building, New York City
R. E. Graham, Chicago, Architect
Hydrated Lime Used Throughout in All Brick Mortar

It is often stated that lime made from dolomite is unsuitable for use in connection with Portland cement because of the high magnesia content. This is not the fact as is shown by the results given in the charts, since these cover tests made on both high calcium and dolomitic limes. It may be stated that the magnesia contained in dolomitic limes shows no deleterious action but on the contrary is a valuable ingredient and contributes to the strength of the mortars.

Proportions for hydrated lime-cement mortar, proportions being given by weight:

BRICK MORTAR

THREE TO ONE MIXTURE—Four bags Portland cement, one bag (100 lbs.) hydrated lime* and 1,500 pounds sand.

FOUR TO ONE MIXTURE—Three bags Portland cement, one bag (100 lbs.) hydrated lime* and 1,600 pounds sand.

FIVE TO ONE MIXTURE—Two bags Portland cement, one bag (100 lbs.) hydrated lime* and 1,500 pounds sand.

STAINLESS CEMENT MORTAR—300 pounds white cement, 100 pounds hydrated lime and 1,200 pounds sand.

FOR TILE SETTING OR ROOFING TILE—85% of Portland cement, 15% of hydrated lime used with 3 parts sand.

CEMENT-HYDRATED LIME MORTAR FOR INTERIOR PLASTERING ON BRICK OR TERRA COTTA:

SCRATCH COAT (OR FIRST COAT)—One bag Portland cement, 2 bags (200 lbs.) hydrated lime and 1,200 pounds sand.

BROWN COAT (OR SECOND COAT)—One bag Portland cement, 2 bags (200 lbs.) hydrated lime and 1,200 pounds sand.

CEMENT MORTARS FOR FIREPROOFING PARTITIONS—100 pounds hydrated lime to 400 pounds Portland cement, and 1,500 pounds sand.

*Hydrated lime is usually sold in 100 lb. burlap or cotton sacks and 40 or 50 lb. paper sacks.

USE OF HYDRATED LIME IN CONCRETE

CHAPTER IX

Plasticity of Hydrated Lime During the time of mixing and placing concrete and up to the time of beginning of the hardening, concrete may be considered as a plastic material. The term plastic as used in reference to concrete and mortar may be defined as that property which allows the material to be cast or moulded into shape. The plastics differ from most materials of construction in that their strength and structural integrity depend to a much greater extent on the skill of the user than upon that of the manufacturer. For example, the quality of concrete is much more dependent on the quality of stone, sand and workmanship than on the quality of Portland cement. In a treatise of this kind it is impossible to discuss in detail how the hardening of the cement is affected by the character of the sand and stone and the method of mixing and placing. It will be readily recognized that the quality of the concrete is largely dependent upon its plasticity—or the ease with which the plastic mass of stone, sand, water and cement will flow into place and assume its final form. This being the case, anything which will improve the plastic quality of the wet mass without materially decreasing its strength after hardening will be found advantageous.

Value in Mortars and Concrete The value of concrete and mortars in construction work depends upon the ease of manipulating them in a plastic state supplemented by the quality of subsequent hardening to a stone-like mass. It is possible to increase the plasticity by using an excess of water, and this is commonly done. Two defects are introduced by the use of too much water. 1st. There is great danger of a separation between the stone and mortar (sand and cement) if the mixture is too wet, resulting in weak stratified concrete. 2nd. The excess water over and above that required by the cement must be expelled in part by gravity and in part by evaporation. Since the original water occupies space, it follows that its removal results in voids and a non-dense concrete. In large slabs the loss of the water may cause shrinkage and cracks. The addition of a large amount of excess water, while it makes the cement mass easier to pour, always results in a lack of density, thereby producing a weak concrete.

Leader-News Building, Cleveland, Ohio
Chas. A. Platt, Architect
Hydrated Lime Used in All Concrete and Brick Mortar

Dam, White Salmon River, Washington (Under Construction)
10% Hydrated Lime Used in All Concrete

Increased Plasticity of Concrete It is well known that the addition of a small amount of hydrated lime (10% or more by weight, of the Portland cement used) renders the concrete mass much more plastic and that less water is required to make the mass workable. As the results of experiments and practical observation, it has been proven that the small amount of hydrate improves greatly the ease of handling the concrete and that it further results in a denser concrete. The greatest advantage of the use of hydrate is this quality of rendering the concrete mass more plastic. Because of this increased plasticity the same amount of tamping results in a denser concrete.

An illustration of the increase in plasticity of concrete, due to the addition of hydrated lime, recently came to the author's observation. In the construction of a large dam in the Northwest, the quarry and rock-crushing plant were located on a hillside, about 400 feet above the river. Since no good sand was available, the fine part of the aggregate was manufactured from the rock. The concrete mixing plant was also located on the hill, above the crest of the dam, and practically all the concrete was spouted into place through chutes about 285 feet long, which had an inclination of 18°. In this manner about 30,000 cu. yds. of concrete was placed. The concrete used was a 1:3:5 mix, using cement, sand and stone, with an addition of 10% hydrated lime. Without the addition of the hydrate, the wet concrete would not flow in chutes, but would dam up and then spill over the side. With the addition of hydrate, the material flowed smoothly and there was very little separation of the mortar from the stone. Throughout the construction of the whole dam, test cylinders were made, 6″ in diameter × 12″ long, and these were broken at regular intervals. These cylinders were made at the site of the dam from the material being deposited. The result showed a considerable improvement both in the quality and the strength of the concrete, due to the hydrated lime.

Retention of Sufficient Moisture to Prevent Shrinkage Cracks in Concrete It is a well known fact that lime paste tends to retain the water mechanically mixed with it. This quality of hydrated lime is particularly valuable when the concrete is spread out in a thin sheet with one surface exposed to the air, as is the case in concrete floors, sidewalks and roads. Practical experience has shown that the more rapidly the mass dries, the greater the likelihood of cracking. This cracking has been attributed to the fact that the rate of surface evaporation is greater than the flow of water from the interior to the surface, causing unequal drying, a condition which gives rise to strain and more or less marked ruptures. During

Dam, White Salmon River, Washington (Completed)

Concrete Road, Garret Co., Maryland
10% Addition of Hydrated Lime to 1-2-4 Concrete
(Monolithic Type)

the early period of drying out and until the concrete has set and hardened, it has little or no strength, and its cohesion is negligible. In this condition it is evident that the slightest shrinkage must result in the formation of cracks. Even though the cracks be so small as to be scarcely noticeable, they are a source of weakness when the hardened concrete is subject to tensile strains. The prevention of the formation of shrinkage cracks is not so important in mass concrete subject only to compression or in reinforced concrete where the tension is provided for by the steel reinforcement, but when used in a thin slab as is the case in concrete roads and pavements, it is very important to reduce the cracks due to shrinkage to a minimum. The addition of a small amount of hydrate to the concrete mass reduces the formation of shrinkage cracks by rendering the mass denser and thereby retarding the evaporation. Further, by rendering the mass more plastic, it prevents the separation of the mortar from the stone, thus producing a more uniform mass. In some recent road work in which 10% of hydrated lime was used throughout the concrete, it was found that fewer cracks developed in this road than in sections having the same composition but in which no hydrate was used.

Armory, York, Penna.
Hydrated Lime Used in Concrete, Brick Mortar and for Scratch, Brown and Finish Coat Plastering.

METHODS OF WATERPROOFING CONCRETE

Concrete can be rendered water-tight in a number of ways:

1. By carefully grading and proportioning the aggregate and the cement.

2. By the application of layers of materials impervious to water, such as asphalts, bitumen, etc., with or without cloth or felt.

3. By plastering the outside surface of the concrete with a rich Portland cement mortar.

4. By the introduction of some foreign material or materials into the mixture.

Ignoring the methods mentioned under Nos. 2 and 3, which both depend for their water-proofing quality upon a layer of material impervious to water, thus keeping the water away from the concrete itself, but which do not render the concrete mass impervious to water, we will deal only with Nos. 1 and 4. The greatest objection to the use of impervious materials such as asphalt, bitumen, etc., either with or without felt or cloth, is the durability of the materials themselves. In a few years, most, if not all, of these substances oxidize, disintegrate and become porous.

Method No. 1 depends on selecting materials which are so graded that they give the densest possible concrete. This method is fully described in Taylor and Thompson's book on "Concrete, Plain and Reinforced." The method requires a careful selection of the sand and stone, careful proportioning of the same, and extreme care in mixing and placing.

NECESSARY QUALIFICATIONS FOR WATERPROOFING MATERIAL

It would be a great advantage to engineers if some method of rendering concrete more impervious to water were known. Thus, if some ingredient could be added to the concrete mass to produce this, the advantage would be apparent. Such an ingredient should possess the following characteristics:

1. It should be easily mixed with the materials forming the concrete aggregate.

2. It should not in any way injure the character of the concrete or have a deleterious action on the cement.

3. It should be preferably of a character chemically similar to that of the cement.

4. It should not be subject to alteration, decomposition or decay, and should be a mineral compound rather than organic.

5. The material should be bulky and preferably of a colloidial nature, so as to fill the interstices of the concrete mass.

6. It should not be so expensive as to make the cost of the concrete excessive.

7. It should be easily procurable and handled.

In looking over these requirements, it will be seen that such materials as oils, waxes and other organic bodies do not fulfill the specifications. They are not of a character similar to the cement, are not easily mixed with the concrete aggregate, and, as they are organic, are subject to alteration and decay. Most of the so-called water-proof compounds on the market at the present time which are to be incorporated in the concrete mass itself contain organic bodies, such as the lime salts of fatty acids, oils, paraffin or Japanese wax, either alone or in combination with other ingredients. While the action of these bodies is to render the concrete mass in the early stages less impervious to water, it is doubtful how long this beneficial action will continue.

In a report of the committee on water-proofing rendered to the American Society for Testing Materials and published in the Proceedings for 1907, the following statement is made:

"The only conclusion possible at the time, from data so far obtained, indicates that the majority of waterproofing compounds examined under the jurisdiction of sub-committee A, are no more effective than untreated properly proportioned mixtures which certainly can be made absolutely water-proof by the use of proper materials and well proportioned mixtures."

Experiments made under the author's direction confirm these conclusions as applying to water-proof compounds which contain organic materials.

Hydrated Lime as a Waterproofing Material

Referring again to the specifications, it will be seen that a material to meet the requirements fully should have a mineral base and should be composed chiefly of lime so as to be similar to cement in its chemical characteristics. It would, therefore, seem that hydrated lime would be a material which would most nearly fill the requirements. Clay has been suggested as a suitable material, but its use in practice would be impracticable owing to the tendency of its particles to adhere, forming balls; these balls have little adhesion, and hence injure the strength of concrete.

RESERVOIR AT WALTHAM, MASSACHUSETTS
FIVE PER CENT. OF HYDRATED LIME ADDED BY WEIGHT OF CEMENT

The following results of tests are given to illustrate the water-proofing properties of hydrated lime:

TENSILE STRENGTH LBS. PER SQUARE INCH*
1-3 Tests   Water Exposure

Age of Test Piece	.95 P. C. .05 L. 3 Sand	.90 P. C. .10 L. 3 Sand	.85 P. C. .15 L. 3 Sand	.80 P. C. .20 L. 3 Sand	.75 P. C. .25 L. 3 Sand	.70 P. C. .30 L. 3 Sand
7 days	157	189	239	237	173	173
28 days	311	364	264	268	259	268
3 months	389	419	372	374	314	281
6 months	321	341	278	260	207	253
9 months	301	308	279	268	250	232
12 months	336	311	322	299	260	231

NOTE—P. C., Portland Cement; L., Hydrated Lime.
Percentage of Hydrated Lime is by weight of Portland cement

These results indicate that quite large additions of hydrated lime can be made to cement mortars even when they are exposed to the action of water. The hydrated lime in this instance acts as a filling material, and as it is of a colloidial nature should render the mortar more impervious to water.

In order to investigate this water-tight character of mortar, circular pats were made of the different mixtures 3″ in diameter and 1″ thick.

*Lazell—Proceedings American Society for Testing Materials, 1908.

These were then placed in an apparatus in such a manner that the water could act upon them in the centre through an opening exactly 2″ in diameter. Thus the area acted upon is 3.1416 square inches.

All pats were subjected to a pressure of thirty pounds for one hour.

PERMEABILITY TESTS 1-3 MIXTURES*

Composition of Test Piece	Amount of water passing through test piece in one hour under 30 lb. head, in cubic centimeters — Age of Test Piece: 7 days	28 days	Remarks
1 P. C. 3 Sand	10 cc	0	
.95 P. C. .05 Hydrate 3 Sand	5 cc	0	Equivalent to replacing 5% of the cement by Hydrate
.90 P. C. .10 Hydrate 3 Sand	2 cc	0	Equivalent to replacing 10% of the cement by Hydrate
.85 P. C. .15 Hydrate 3 Sand	0.3 cc	0	Equivalent to replacing 15% of the cement by Hydrate

NOTE—P. C. Portland Cement.

Percentage of lime is in terms of weight of cement.

PERMEABILITY TESTS. 1-5 MIXTURES

	28 days	6 Weeks	Remarks
1 P. C. 5 Sand	3000 cc	1090 cc	
.95 P. C. .05 Hydrate 5 Sand	5 cc	3 cc	Equivalent to replacing 5% of the cement by Hydrate
.90 P. C. .10 Hydrate 5 Sand	2.5 cc	0	Equivalent to replacing 10% of the cement by Hydrate
.85 P. C. .15 Hydrate 5 Sand	0	0	Equivalent to replacing 15% of the cement by Hydrate

NOTE—P. C., Portland Cement.

Percentage of lime is in terms of weight of cement.

*E. W. Lazell—Proceedings American Society for Testing Materials, 1908.

Referring to the preceding tests it will be seen that the addition of even small amounts of hydrated lime to mortar materially increases its water-tightness.

Sanford E. Thompson,* in an address delivered before the American Society for Testing Materials, in June, 1908, gave tests upon the concrete used for the Waltham, Mass., reservoir as follows:

"A few permeability tests with hydrated lime admixtures made by the writer in 1903 indicated it to be a valuable material for water-proofing. Later in 1906 when the reservoir at Waltham, Mass.,** which is 100 feet in diameter and 43 feet high, was under consideration, the writer was consulted by Bertram Brewer, City Engineer, in the framing of the specifications and made another series of tests as follows:

Permeability Test of 1:2:4 Concrete for Waltham, Mass., Reservoir, 1906
Concrete 4 in. thick. Pressure 80 lbs. per sq. in.

Percentage of Hydrated Lime	Flow in Grams per minute		
	At 14 days	At 21 days	At 28 days
0%	5.52	2.92	1.91
2%	9.20	2.55	1.63
4%	2.82	1.49	0.76

Percentage of lime is in terms of weight of cement.

"This flow is much greater than in the tests described at Cambridge, but the pressure in the Cambridge tests is about one-third higher, the age is greater, and probably, most important of all, the thickness of concrete is twice as great.

"As a result of those tests for Waltham, 5% of hydrated lime was adopted for the reservoir to mix with the 1:2:4 concrete in building its walls. The results were satisfactory, the only seepage occurring at joints formed between different day's work, where the bond between the old and the new concrete was not made with sufficient care."

†In a recent address by Sanford E. Thompson, given before the American Society for Testing Materials, in June, 1908, he discussed a series of tests made on concrete composed of Portland cement, sand and stone in varying proportions to which had been added varying amounts of hydrated lime. In making these tests, concrete cubes were used containing an embedded pipe through which the water pressure could be applied. The results are given in the table on following page:

*Engineering Record June 27, 1908.

**Engineering Record January 12, 1907, Page 32.

†Engineering Record June 27, 1908.

		Flow of water under 7-ft. head			Flow under pressure of 60 lbs. per sq. in.			
Mark	Per cent. Hydrated Lime	Age	Duration of measured flow	Flow Grams per Hour	Age	Pressure applied before measure	Duration of measured flow	Flow Grams per Hour
		Days	Hours		Days	Hours	Hours	
1:2:4 concrete								
No.1	1%	18	161	2.7	40	24	$4\frac{1}{4}$	74.8
No. 2	4%	18	161	1.2	41	18	5	28.4
No. 3	7%	18	161	1.0	42	18	$6\frac{3}{4}$	5.2
No. 4	10%	15	161	1.0	46	6	18	1.6
$1:2\frac{1}{2}:4\frac{1}{2}$ con.								
No. 5	0%	30	169	0.3	44	17	6	1.1
No. 6	0%	30	169	1.9	45	18	6	32.5
No. 7	10%	29	169	0.8	49	..	11	0
No. 8	14%	29	169	0.7	50	..	27	0
1:3:5 concrete								
No. 9	0%	26	169	9.8	50	6	14	70.6
No. 10	8%	26	169	1.1	51	8	17	3.6
No. 11	14%	28	169	1.1	50	28	13	10.7
No. 12	20%	28	169	1.2	53	9	15	0.7

"The percentages of hydrated lime are based on the weight of the cement, these being added to the cement and not replacing it. The variations in the ages of the specimens in different proportions slightly affects the results and accounts in part for the fact that the 1:3:5 mixtures in the pressure tests are nearly as water-tight as the richer proportions. Specimen No. 5, which shows practically no flow, is evidently erratic."

He concludes from these experiments as follows:

"(1) Hydrated lime increases the water-tightness of concrete.

"(2) Effective proportions of hydrated lime for water-tight concrete are as follows:

"For one part Portland cement: 2 parts sand: 4 parts stone, add 8 per cent hydrated lime.

"For 1 part Portland cement: $2\frac{1}{2}$ parts sand: $4\frac{1}{2}$ parts stone, add 12 per cent hydrated lime.

"For 1 part Portland cement: 3 parts sand: 5 parts stone, add 16 per cent hydrated lime.

"These percentages are based on the weight of the dry hydrated lime to the weight of the dry Portland cement.

"(3) The cost of large waterproof concrete structures frequently may be reduced by employing leaner proportions of concrete with hydrated lime admixtures, and small structures, such as tanks, may be made more water-tight.

"(4) Lime paste made from a given weight of hydrated lime occupies about $2\frac{1}{4}$ times the bulk of paste made from the same weight of Portland cement, and is therefore very efficient in void filling.

Ambursen Hollow Dam, Near Portland, Oregon

Hydrated Lime Used for Waterproofing the Deck Slabs

"Although the character of the sand and stone used in the concrete will affect the best percentage of lime to use, the present materials are representative of average materials throughout the country so that the results should be of general application. Coarser sand would naturally require slightly larger percentages of lime and finer sand, that is, sands having a larger percentage of fine grains, which pass a sieve with 40 meshes to the linear inch, would be apt to require less lime since sands containing considerable fine material produce a more water-tight although a weaker concrete."

In these experiments of Thompson a water pressure of 60 pounds to the square inch was used, which is equivalent to a head of about 140 feet. This is more severe than is encountered in the general engineering practice.

The conclusions to be drawn from the investigations given indicate that in hydrated lime we have the best material at present known for rendering concrete water-tight. Hydrated lime, however, must not be confounded with quick-lime, which is absolutely unfit to be used in concrete. The effect of the addition of hydrated lime in small quantities is mostly mechanical, filling the voids, thus making the concrete impervious to water. The quantity which should be used depends upon the fineness of the sand employed and the proportions of the mixture. The concrete materials must be properly graded, the proper proportions of cement and hydrated lime used. Even with this preliminary care, if the concrete is poorly mixed with insufficient water, or improperly placed, or if joints are left, the walls will inevitably leak. The mixing must be thorough; sufficient water must be employed to give a "mushy" mixture so that it will settle into place with the least amount of ramming. Fully as important as the care in mixing is the bonding of one day's concrete with the next; even small interruptions of an hour on a hot day will materially injure the bond of the concrete. It is, therefore, necessary that if water-tight work is to be done, the greatest care should be exercised both in the selection of the materials, proportions of the ingredients, mixing and placing the same. Hydrated lime can be advantageously used only in mixtures as lean or leaner than 1-2-4 unless the hydrated lime is substituted for an equal weight of cement. Ten per cent by weight of the cement has been found a convenient amount in a number of instances. Hydrated lime is a bulky material, the same weight occupying about two and one-half times the volume of the same weight of cement.

HOTEL OREGON, PORTLAND, OREGON

DOYLE-PATTERSON, ARCHITECTS

Hydrated Lime Used in Concrete and Brick Mortar

ADVANTAGES OF HYDRATED LIME OVER OTHER FORMS OF LIME.

CHAPTER X

HYDRATED lime is generally purer than the quick lime from which it is made. Chapter VIII, Page 50.

Hydrated lime is easily subjected to inspection and tests, and the same material is tested as is used. Chapter VIII, Page 50.

The use of hydrated lime does away with the slaking of lump lime, hence saves the cost and the space required for this operation. Chapter VIII, Page 50.

Hydrated lime is thoroughly slaked and this fact can be determined by tests. Chapter VIII, Page 50.

By the use of hydrated lime mortar definite proportions can be maintained. This is a difficult matter with lump lime. Chapter VIII, Page 49. Table Page 53.

The putty or mortar made with hydrated lime requires no aging to be assured of thorough slaking. The Romans recognized the necessity of long aging for lime paste and an old Roman law required that lime be slaked three years before using. In the south of Europe at the present time it is the custom to slake lime the season before it is used. Chapter V, Page 38.

Hydrated lime can be economically mixed by means of a mortar mixer. Chapter VIII, Page 52.

Mortars made from hydrated lime are stronger than mortars made from lump lime slaked to a paste. Chapter VIII, Pages 57 to 60.

Hydrated lime can be mixed with cement mortar or concrete in any desired proportions. It is a very difficult matter to mix lime paste with cement thoroughly. Chapter VIII, Page 56.

Hydrated lime can be stored without danger of fire. No heat is generated when water comes in contact with hydrate.

Hydrated lime is not apt to be spoiled by air slaking, as is the case with lump lime. Often large amounts of lime are lost in this manner.

Hydrated lime comes into the market in packages of definite weight and convenient size.

The paper sacks generally used cost less than half as much as the barrels required to hold an equal weight of lump lime.

The paste made from hydrated lime requires no screening.

There is no loss in the form of "core" when hydrated lime is used.

Against all these advantages only two objections are obvious. One, the mortar made from hydrated lime often works harder and is less plastic than that made from lump lime. This difficulty is generally greatly exaggerated. Second, hydrated lime will not carry so much sand as a corresponding weight of lump lime. This fact has been explained on page 52.

The second objection is dependable upon the first, because the larger sand carrying capacity of lump lime paste is due to its plasticity, or buttery, easy working quality. This quality of lump lime usually results in the addition of too much sand. The oversanding of lime mortar is very generally practiced, since it is the custom to add as much sand as possible in order to cheapen the cost of the mortar. This results in a lean, oversanded mortar possessing little strength. The manufacturers of lime are not blameless in this respect, since they have educated the public to believe that the greater the yield of paste from a barrel of lime the more sand it will carry, overlooking the fact that a leaner lime, or one which does not yield as great a volume of paste, produces a much stronger mortar.

The increase in bulk when lime is slaked is mostly due to the water mechanically absorbed. When the lime mortar hardens, this water evaporates, causing it to shrink and the excess water is therefore a source of weakness and not strength. The greater the amount of water held mechanically, the greater the volume of the paste, and therefore the less the amount of binding ingredient or lime contained in a volume of paste. This point is brought out clearly from the table on page 35.

It has been proven by many experiments that the poorer limes make the stronger mortars. These poor, or lean limes contain clay, which unites with the lime during the process of burning, and the presence of this clay imparts some hydraulic or hardening properties to the mortar. These hydraulic limes are largely used in Europe, but, unfortunately, little of this material has been manufactured in this country. Practically the same results can be obtained by the use of a mixture of hydrated lime and Portland cement.

From all the advantages possessed by hydrated lime it would appear to be the best form of lime to be used. It is perfectly logical that the process of slaking should be taken away from the haphazard manner used on the work and done at the point of manufacture of the lime where skillful supervision is possible.

APPENDIX I.

Useful Data—Lime.

DEFINITION—Lime is the product resulting from calcining (burning) of limestone, which slakes upon the addition of water.

WEIGHT—Lump lime weighs from 50 to 60 pounds per cubic foot.

BARREL—A 200 pound barrel of lime contains 185 pounds net of lump lime, or 3.1 cubic feet.

A 300 pound barrel of lime contains 280 pounds net of lime or 4.7 cubic feet.

BUSHEL—A bushel of lime is from 75 to 80 pounds, depending upon the law in the state in which the lime is purchased.

A bushel contains from 1 to 1.3 cubic feet.

PASTE—Lime paste is a mixture of slaked lime and water.

SLAKING—A pound of high calcium lime requires from 1 to 1½ pounds of water to form a paste.

A pound of dolomitic lime requires about 1 pound of water to form a paste.

A barrel of high calcium lime requires from 30 to 40 gallons of water to produce a paste.

A barrel of dolomitic lime requires from 25 to 30 gallons of water to produce a paste.

SLAKING—Slaking is the most important operation in preparing mortar.

BURNING—Lime must not be burned in slaking.

Burning results from the use of too little water or insufficient mixing during slaking.

DROWNING—Lime must not be drowned in slaking.

Drowning results from the use of too much water.

AGING—Lime used for plastering should be slaked at least 3 weeks before using. The longer the paste is aged the better the quality of the mortar.

VOLUME OF PASTE—A barrel of lime gives from 6 to 9 cubic feet of paste; average about 7½ cubic feet.

Hydrated Lime.

DEFINITION—Hydrated lime is a dry, specially prepared slaked lime.

WEIGHT—Hydrated lime weighs from 36 to 45 pounds per cubic foot; average about 40 pounds.

SACK—A 100 pound sack of hydrated lime contains about 2½ cubic feet.

PASTE—It requires about an equal weight of water to produce a paste. A 100 pound sack of hydrate gives about 2.3 cubic feet of paste of ordinary consistency.

Portland Cement.

DEFINITION—Portland cement is made from a mixture of materials containing lime and clay.

WEIGHT—A barrel of Portland cement weighs 376 pounds net, and contains 3.8 cubic feet.

A bag of Portland cement weighs 94 pounds and contains about 1 cubic foot.

PACKED—Packed cement weighs on the average 115 pounds to the cubic foot.

LOOSE—Loose Portland cement weighs on the average 92 pounds to the cubic foot.

CUSTOMARY WEIGHT—In general a sack of cement is considered to be 1 cubic foot and to weigh 100 pounds.

PASTE—Cement paste is a mixture of cement and water.

WEIGHT OF PASTE—Cement paste weighs about 137 pounds to the cubic foot.

Sand.

QUALITY—The quality of sand is chiefly dependent upon the coarseness and the relative size of the grains.

CLAY OR LOAM—Clay or loam in sand is often injurious to mortar because too much fine material is introduced.

SPECIFIC GRAVITY—Specific gravity of sand is about 2.65.

WEIGHT—Sand weighs from 80 to 120 pounds to the cubic foot, average about 100 pounds.

COARSE SAND—Coarse sand requires less water than fine sand and gives a stronger mortar.

MIXED SAND—Mixed sands usually weigh more and contain a smaller volume of voids than coarse or small sands.

FINE SAND—Fine sand with grains of uniform size weighs nearly the same when dry and has nearly the same percentage of voids as screened sand. Fine sand with ordinary moisture is lighter and more porous than coarse sand.

VOIDS—Voids are the spaces in a mass of sand or mortar that are filled with water or air.

Vegetable Matter—Even a small amount of vegetable matter present in sand may result in a weak mortar.

Mortar.

Definition—Mortar is a mixture of sand and water with some binding material, such as lime, cement, or both.

Strongest Mortar—Is obtained from those sands which produce the smallest volume of plastic mortar.

Fine Sands—Always produce a mortar of less strength than coarse sands.

Mixtures of Fine and Coarse Sands—Often produce a stronger mortar than either material alone.

Clay or Loam—In sand generally weakens a rich mortar and may strengthen a lean mortar.

Weight—The weight of lime or cement mortar varies with the proportions as well as with the materials of which it is composed. Average weight of lime mortar is about 120 pounds per cubic foot. Average weight of 1-3 cement mortar is 135 pounds per cubic foot.

Proportions—Proportions must be accurately measured.

Mixing—Mixing must be thorough. All mortars are improved by long mixing.

Machine Mixing—Machine mixing is better than hand mixing and gives more plastic mortar.

Quantities.

Average Wooden Wheelbarrow Load of broken stone is about 2.4 cubic feet.

Average Wooden Wheelbarrow Load of sand is about 2½ cubic feet.

Average Iron Wheelbarrow Load of stone or gravel is about 3 cubic feet.

Average Iron Wheelbarrow Load of sand is about 3½ cubic feet.

Shovel—A No. 2 shovel holds about 15 pounds of sand.
A No. 3 shovel holds about 18 pounds of sand.
A No. 4 shovel holds about 20 pounds of sand.

Bucket—A 3 gallon (12 quart) bucket holds 16 pounds of hydrate.
A 3 gallon (12 quart) bucket holds 35 pounds of sand.
A 3 gallon (12 quart) bucket holds 40 pounds of cement.

APPENDIX II.

Standard Specifications for Hydrated Lime*

SERIAL DESIGNATION: C6-15.

The specifications for this material are issued under the fixed designation C6; the final number indicates the year of original issue, or in the case of revision, the year of last revision.

ADOPTED, 1915.

1. DEFINITION.—Hydrated lime is a dry flocculent powder resulting from the hydration of quicklime.

2. CLASSES.—Hydrated lime is commercially divided into four classes:
   (a)—High-Calcium;
   (b)—Calcium;
   (c)—Magnesian;
   (d)—High-Magnesian.

3. BASIS OF PURCHASE.—The particular class of hydrated lime desired shall be specified in advance by the purchaser.

I. CHEMICAL PROPERTIES AND TESTS.

4. SAMPLING.—The sample shall be a fair average of the shipment. Three per cent of the packages shall be sampled. The sample shall be taken from the surface to the center of the package. A 2-lb. sample to be sent to the laboratory shall immediately be transferred to an air-tight container, in which the unused portion shall be stored until the hydrated lime has been finally accepted or rejected by the purchaser.

5. CHEMICAL PROPERTIES.—(a)—The classes and chemical properties of hydrated lime shall be determined by standard methods of chemical analysis.
   (b)—The non-volatile portion of hydrated lime shall conform to the following requirements as to chemical composition:

*Authorized reprint from the copyrighted Year Book for 1915 of the American Society for Testing Materials, Philadelphia, Pa., U. S. A.

CHEMICAL COMPOSITION

Properties Considered.	High-Calcium	Calcium	Magnesian	High-Magnesian
Calcium Oxide, per cent..........	90 (min.)	85–90	....	....
Magnesium Oxide, per cent.......	....	....	10–25	25 (min.)
Silica plus Alumina plus Oxide of Iron, max., per cent..........	5	5	5	5
Carbon Dioxide, max., per cent....	5	5	5	5
Water........................	Sufficient to hydrate the calcium-oxide content	Sufficient to hydrate the calcium-oxide content	Sufficient to hydrate the calcium-oxide content	Sufficient to hydrate the calcium-oxide content

II. PHYSICAL PROPERTIES AND TESTS.

6. Fineness.—A 100-g. sample shall leave by weight a residue of not over 5 per cent on a standard 100-mesh sieve and not over 0.5 per cent on a standard 30-mesh sieve.

7. Constancy of Volume.—Hydrated lime shall be tested to determine its constancy of volume in the following manner:

Equal parts of hydrated lime under test and volume-constant Portland cement shall be thoroughly mixed together and gauged with water to a paste. Only sufficient water shall be used to make the mixture workable. From this paste a pat about 3 in. in diameter and ½ in. thick at the center, tapering to a thin edge shall be made on a clean glass plate about 4 in. square. This pat shall be allowed to harden 24 hours in moist air and shall be without popping, checking, cracking, warping or disintegration after 5 hours' exposure to steam above boiling water in a loosely closed vessel.

III. PACKING AND MARKING.

8. Packing.—Hydrated lime shall be packed either in cloth or in paper bags and the weight shall be plainly marked on each package.

9. Marking.—The name of the manufacturer shall be legibly marked or tagged on each package.

IV. INSPECTION AND REJECTION.

10. Inspection.—(a)—All hydrated lime shall be subject to inspection.

(b)—The hydrated lime may be inspected either at the place of manufacture or the point of delivery, as arranged at the time of purchase.

(c)—The inspector representing the purchaser shall have free entry at all times while work on the contract of the purchaser is being performed, to all parts of the manufacturer's works which concern the manufacture of the hydrated lime ordered. The manufacturer shall afford the inspector all reasonable facilities for inspection and sampling, which shall be so conducted as not to interfere unnecessarily with the operation of the works.

(d)—The purchaser may make the tests to govern the acceptance or rejection of the hydrated lime in his own laboratory or elsewhere. Such tests, however, shall be made at the expense of the purchaser.

11. Rejection.—Unless otherwise specified, any rejection based on failure to pass tests prescribed in these specifications shall be reported within five working days from the taking of samples.

12. Rehearing.—Samples which represent rejected hydrated lime shall be preserved in air-tight containers for five days from the date of the test report. In case of dissatisfaction with the results of the tests, the manufacturer may make claim for a rehearing within that time.

APPENDIX III.

QUANTITIES OF MATERIALS FOR ONE CUBIC YARD OF PLASTIC MORTAR HYDRATED LIME MORTAR

One bag of hydrate equals 100 pounds, 2½ cubic feet

TABLE No. 1

Parts by Volume

Proportions By Parts		Proportions By Volume		Volume of Mortar from One Bag	Quantities of Materials to Make 1 Cubic Yard of Mortar	
Hydrate	Sand	Hydrate Bags	Sand Cu. Ft.	Cu. Ft.	Hydrate Bags	Sand Cu. Yds.
1	1	1	2.50	3.44	7.84	0.73
1	1½	1	3.75	4.61	5.85	0.81
1	2	1	5.00	5.79	4.66	0.86
1	2½	1	6.25	6.97	3.87	0.89
1	3	1	7.50	8.15	3.31	0.92
1	3½	1	8.75	9.32	2.90	0.94
1	4	1	10.00	10.50	2.57	0.95
1	4½	1	11.25	11.67	2.31	0.96
1	5	1	12.50	12.85	2.10	0.97

Notes—Variations in the fineness of the sand and in the consistency of the mortar may affect the yield of mortar by 10% in either direction.

Hydrated Lime requires about its own weight of water to be reduced to a paste. The volume of this paste is about 90% of the volume of dry hydrate.

The volume of mortar refers to its volume in a plastic condition as mixed, not to its volume after ramming or hardening.

TABLE No. 1-A

Parts by Weight

Proportions By Parts		Proportions By Volume		Volume of Mortar from One Bag	Quantities of Materials to Make 1 Cubic Yard of Mortar	
Hydrate	Sand	Hydrate Bags	Sand Cu. Ft.	Cu. Ft.	Hydrate Bags	Sand Cu. Yds.
1	1	1	1	2.00	13.50	0.50
1	1½	1	1½	2.46	10.96	0.61
1	2	1	2	2.94	9.19	0.68
1	2½	1	2½	3.44	7.84	0.73
1	3	1	3	3.89	6.93	0.77
1	3½	1	3½	4.37	6.17	0.80
1	4	1	4	4.83	5.59	0.83
1	4½	1	4½	5.31	5.08	0.85
1	5	1	5	5.79	4.66	0.86

QUANTITIES OF MATERIALS FOR ONE CUBIC YARD OF PLASTIC MORTAR.
HYDRATED LIME MORTAR WITH ADDITION OF PORTLAND CEMENT.

TABLE No. 2

Parts by Volume

Proportions by Parts		Proportions For One Cubic Yard by Volume		Pounds of Portland Cement Required for Each Per Cent. Added				
Hydrate	Sand	Hydrate Bags	Sand Cu. Yds.	5% Lbs.	10% Lbs.	15% Lbs.	20% Lbs.	25% Lbs.
1	2	4.66	0.86	23	46	70	92	115
1	2½	3.87	0.89	19	39	58	78	97
1	3	3.31	0.92	16	32	48	64	83
1	3½	2.90	0.94	15	29	43	58	72
1	4	2.57	0.95	14	27	40	51	64
1	4½	2.31	0.96	12	23	35	46	58
1	5	2.10	0.97	11	22	33	44	54

Notes—Variations in the fineness of the sand and in the consistency of the mortar may affect the yield of mortar by 10% in either direction.

The amount of Portland cement added is a percent of the amount of Hydrate used.

A cubic foot of dry hydrate weighs 40 lbs.

A cubic foot of Portland cement weighs 100 lbs.

TABLE No. 2-A

Parts by Weight

Proportions by Parts		Proportions For One Cubic Yard by Volume		Pounds of Portland Cement Required for Each Per Cent. Added				
Hydrate	Sand	Hydrate Bags	Sand Cu. Yds.	5% Lbs.	10% Lbs.	15% Lbs.	20% Lbs.	25% Lbs.
1	2	9.19	.68	46	92	138	184	230
1	2½	7.84	.73	39	78	118	157	196
1	3	6.93	.77	35	69	104	139	173
1	3½	6.17	.80	31	62	93	123	154
1	4	5.59	.83	28	56	84	111	140
1	4½	5.08	.85	25	51	76	102	127
1	5	4.66	.86	23	47	70	93	116

QUANTITIES OF MATERIALS FOR ONE CUBIC YARD OF PLASTIC MORTAR. CEMENT MORTAR WITH HYDRATED LIME ADDITIONS.

TABLE No. 3

Proportions by Parts, Weight or Volume		Proportions by Volume		Volume Resulting Mortar Cu. Ft.	Quantities to Make 1 Cubic Yard of Mortar		Pounds of Hydrate Required for Each Percent Added				
Cement	Sand	Cement Bbls.	Sand Cu. Ft.	From 1 Bbl. Cement	Cement Bbls.	Sand Cu. Yd.	5% Lbs.	10% Lbs.	15% Lbs.	20% Lbs.	25% Lbs.
1	2	1	7.6	10.0	2.70	.76	50	101	151	202	252
1	2½	1	9.5	11.8	2.29	.81	43	86	129	172	215
1	3	1	11.4	13.7	1.97	.83	38	74	111	148	186
1	3½	1	13.3	15.5	1.74	.86	32	65	97	130	162
1	4	1	15.2	17.3	1.56	.88	29	58	87	116	145
1	4½	1	17.1	19.1	1.41	.89	26	53	79	106	132
1	5	1	19.0	21.0	1.28	.90	24	48	72	96	120

NOTE—Variations in the fineness of the sand and in the consistency of the mortar may affect the yield of mortar by 10% in either direction.

The amount of Hydrated Lime is a percent of the amount of Portland cement used.

QUANTITIES OF MATERIALS FOR ONE CUBIC YARD OF PLASTIC MORTARS HYDRATED LIME-PORTLAND CEMENT MORTAR

Equal Parts of Hydrate and Cement

TABLE No. 4

PARTS BY VOLUME

Proportions by Parts			Proportions by Volume			Volume of Mortar from 1–40 lb. Bag Hydrate and 1 100 lb. Bag Cement Cu. Ft.	Quantities of Materials to Make 1 Cubic Yard		
Hydrate	Cement	Sand	Hydrate 40 Lbs. Bag	Cement 100 Lbs. Bag	Sand Cu. Ft.		Hydrate 40 lb. Bag	Cement 100 lb. Bag	Sand Cu. Yd.
1	1	3	1	1	3	4.18	6.46	6.46	0.72
1	1	4	1	1	4	5.13	5.26	5.26	0.77
1	1	5	1	1	5	6.08	4.44	4.44	0.82
1	1	6	1	1	6	7.03	3.84	3.84	0.85
1	1	7	1	1	7	7.98	3.38	3.38	0.87
1	1	8	1	1	8	8.93	3.02	3.02	0.89
1	1	9	1	1	9	9.88	2.73	2.73	0.91
1	1	10	1	1	10	10.83	2.49	2.49	0.92

NOTE—Variation in the fineness of the sand and in the consistency of the mortar may affect the yield of mortar by 10% in either direction.

The volume of mortar refers to its volume in a plastic condition as mixed, not to its volume after ramming or hardening.

QUANTITIES OF MATERIAL FOR ONE CUBIC YARD OF RAMMED CONCRETE SHOWING ALSO THE AMOUNT OF HYDRATED LIME ADDED

TABLE No. 5

Proportions by Parts			Proportions by Volume			Quantities for One Cubic Yard			Pounds of Hydrated Lime Added for One Yard Mixture				
Cement	Sand	Stone	Cement Bbls.	Sand Cu. ft.	Stone Cu. ft.	Cement Bbls.	Sand Cu. yd	Stone Cu. yd	5% lbs.	10% lbs.	15% lbs.	20% lbs.	25% lbs.
1	1	2	1	3.8	7.6	2.73	0.38	0.77	51	103	154	206	257
1	1	2½	1	3.8	9.5	2.45	0.34	0.86	46	92	138	184	230
1	1	3	1	3.8	11.4	2.20	0.31	0.94	41	83	124	165	206
1	1½	2	1	5.7	7.6	2.40	0.51	0.68	45	90	135	180	225
1	1½	2½	1	5.7	9.5	2.18	0.46	0.77	41	82	123	164	205
1	1½	3	1	5.7	11.4	2.00	0.42	0.84	37	75	113	150	188
1	2	3	1	7.6	11.4	1.81	0.51	0.76	34	68	102	136	170
1	2	3½	1	7.6	13.3	1.68	0.47	0.83	31	63	94	125	156
1	2	4	1	7.6	15.2	1.57	0.44	0.88	29	59	88	117	146
1	2	4½	1	7.6	17.1	1.48	0.42	0.94	28	56	84	112	140
1	2½	3	1	9.5	11.4	1.66	0.58	0.70	31	62	93	124	155
1	2½	3½	1	9.5	13.3	1.55	0.55	0.76	29	58	87	116	145
1	2½	4	1	9.5	15.2	1.46	0.51	0.82	27	55	82	110	137
1	2½	4½	1	9.5	17.1	1.37	0.48	0.87	26	52	78	104	130
1	2½	5	1	9.5	19.0	1.30	0.46	0.92	24	49	73	96	123
1	2½	5½	1	9.5	20.9	1.23	0.43	0.95	23	46	69	92	115
1	2½	6	1	9.5	22.8	1.17	0.41	0.99	22	44	66	88	110
1	3	4	1	11.4	15.2	1.36	0.57	0.77	25	51	76	102	127
1	3	4½	1	11.4	17.1	1.28	0.54	0.81	24	48	72	96	120
1	3	5	1	11.4	19.0	1.22	0.52	0.86	23	46	69	92	115
1	3	5½	1	11.4	20.9	1.16	0.49	0.90	22	44	66	88	110
1	3	6	1	11.4	22.8	1.11	0.47	0.94	21	42	63	84	105
1	3	6½	1	11.4	24.7	1.06	0.45	0.97	20	40	60	80	100
1	3	7	1	11.4	26.6	1.01	0.43	0.99	19	38	57	76	95
1	3	7½	1	11.4	28.5	0.97	0.41	1.02	18	36	54	72	90
1	3	8	1	11.4	30.4	0.93	0.39	1.05	17	35	52	70	87
1	4	5	1	15.2	19.0	1.08	0.61	0.76	20	40	60	80	100
1	4	6	1	15.2	22.8	0.99	0.56	0.84	18	37	55	74	92
1	4	7	1	15.2	26.6	0.92	0.52	0.91	17	34	51	68	85
1	4	8	1	15.2	30.4	0.85	0.48	0.96	16	32	48	64	80
1	4	9	1	15.2	34.2	0.80	0.45	1.01	15	30	45	60	75
1	4	10	1	15.2	38.0	0.75	0.42	1.06	14	28	42	56	70
1	5	10	1	19.0	38.0	0.69	0.49	0.97	13	26	39	52	65

NOTES—The above table for quantities of cement has been taken from Taylor & Thompson's "Concrete, Plain and Reinforced." The quantities of hydrated lime have been calculated by the author.

In many instances the amounts are even fractions of a sack of hydrate (100 lbs.), i. e., 10% in a 1-2-4 is practically half a sack.

In case where the amount of hydrate called for is not a convenient part of a sack, it is advisable to have a box made which will hold the required amount. This is easily done, as a cubic foot of hydrate weighs 40 lbs. A one sack mixture would require the addition of ¼ the amount of materials and a 2 sack mixture of ½ the amount.

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Date Due

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